AFIT/GOR/ENS/99M-03

QUALITY FUNCTION DEPLOYMENT

FROM AN

OPERATIONS RESEARCH PERSPECTIVE

THESIS

Eve M. Burke, First Lieutenant, USAF

AFIT/GOR/ENS/99M-03

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THESIS

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Eve M. Burke

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ABSTRACT

The methodology of Quality Function Deployment (QFD) is compared to operations analysis standards. Of special concern is how Air Combat Command (ACC) uses QFD for the Modernization Planning Process (MPP). ACC digresses from the traditional use of QFD for incorporating quality into manufacturing processes to use it as a planning tool. ACC's goal in implementing QFD is to incorporate the demands of the Air Force mission into the modernization planning effort. ACC's use of QFD to identify and quantify current deficiencies and quantify the value of alternative future solutions has led to the investigation of inconsistencies with QFD, both generally and with how ACC employs it. In short, the purpose of this thesis is to improve ACC's current method for optimizing combat capability through both near-term and far-term modifications.

QUALITY FUNCTION DEPLOYMENT

FROM AN

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Chapter 1

INTRODUCTION

In today's world with new markets continually emerging, there is an ever-increasing demand for better technology and faster, more efficient products and services. Both the commercial and especially the military sectors must deal with doing more with less money. "We must continue to seek new, revolutionary, and imaginative ways to employ air and space power and continue to provide the United States with even more capability to pursue national and military objectives with reduced risk and cost in casualties, resources, and commitment" (AFDD 1, 1997: 40). In the military, there is a growing need for greater efficiency in planning, programming and budgeting for necessary capabilities while maintaining near term capabilities necessary to meet current objectives.

There are numerous disciplines and techniques in the management and operational sciences arenas that could be usefully applied to the types of problems both military and commercial organizations face. "The Air Force must continually refine the objectives and tasks of its mission areas and support functions to reflect changes in national military strategy, global political-military threats, and fiscal constraints" (AFPD 10-14, 1995: 1). The Air Force (AF) has developed the Modernization

Planning Process (MPP), which forms the foundation of the Air Force 25-year plan for requirements, programming, and budgeting decisions to meet Air Force goals. The MPP guides the Major Commands (MAJCOMs), product centers, and laboratory staffs in efficiently planning, programming and budgeting. The ultimate purpose of the process is to plan for the acquisition of materiel solution upgrades to the Air Force force structure (ASC/XR, 1997: 1). "The idea behind the AFMPP is to provide a standardized process that yields a bidirectionally traceable logic flow from national strategy to the technologies necessary to build the weapon systems to implement the military portions of that strategy" (ASC/XR, 1997: 7). The MPP utilizes an extended version of the strategy-to-task (STT) framework created by General Kent in 1989 called the "Strategy to Technology Method" for defining and responding to materiel deficiencies in the AF force structure.

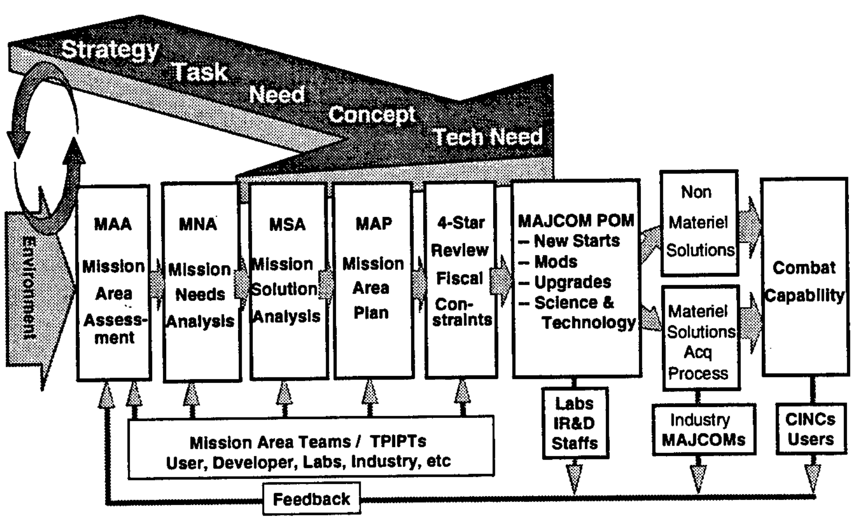


Figure 1: The Modernization Planning Process (ASC/XR, 1997: 6)

Figure 1 shows an overview of the format of the MPP. The intent of modernization planning is to provide guidance for changing doctrine, tactics, training and procedures and investing scarce dollars (AFPD 10-14, 1995: 1). It is essentially the first "P" in the Planning, Programming and Budgeting System (PPBS). The MPP has three major phases. First, the Mission Area Assessment (MAA) phase identifies the operational tasks the Commander in Chiefs (CINCs) may ask warfighters to execute. The MAA phase conducted by Air Combat Command (ACC) lays out the STT framework that forms the foundation for the entire process. STT is based on Defense Planning Guidance (DPG), Air Force Doctrine Document (AFDD 1), Air Force Executive Guidance, AF Vision and long-range plan, theater command input, regional operations orders, and operational plans (HQ ACC, Modernization Investment Plan (MIP) Handbook, 1998: A-4). STT is essentially the hierarchical decomposition of national goals. Figure 2 is a miniature example of a STT hierarchy. Notice the hierarchy extends beyond the operational tasks all the way to solutions (concepts) eventually leading to a "relative combat capability weight" for each modernization initiative.

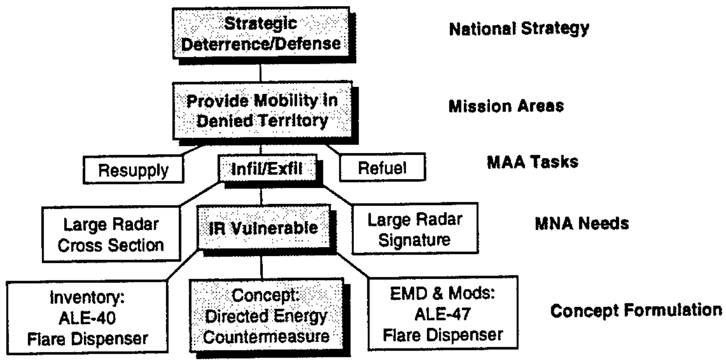


Figure 2: Strategy to Task to Concept Example (ASC/XR, 1997: 37)

The second phase in the MPP, the Mission Needs Analysis (MNA), looks at the mission needs and assesses how well the Air Force currently executes them. The MNA phase is an effort to determine how well the Air Force can accomplish its mission, and point out any deficiencies. Third, the Mission Solution Analysis (MSA) identifies potential solutions for improving the execution of the Combat Air Forces' (ACC, PACAF, USAFE, ANG, and AFRES) needs and evaluates the benefit (contribution to combat capability) and cost of each solution to determine the best investment strategy. The solutions could be repairs, modifications or new programs designed to help correct the capability shortfalls identified during the MNA (HQ ACC, MIP Handbook, 1998: A-13). The MPP is an iterative process and the activities performed in each phase are accomplished simultaneously.

Currently, ACC uses Quality Function Deployment (QFD) in their interpretation of the MPP. QFD is a structured process that uses a team approach to *identify* and *prioritize* customer requirements and translate these requirements into appropriate

company *(Air Force)* requirements at each stage of the product life cycle (HQ ACC/DRA, MPP Overview, 1998: 3). The idea of incorporating quality into processes and products has always been an element of commerce from prehistory. It is manifest in recent centuries in the form of family commercial facilities, apprentice programs and guild standards. Quality has been embraced in the last few decades as an essential element of modern management. QFD was first systematized in the early-1970s at Kobe Shipyard, Mitsubishi Heavy Industries, Ltd. It is intended to guide companies in developing and customizing their own approach to quality in product development (Akao, 1990: xiv).

QFD is an excellent management tool for providing guidance and insight into an organization's process while incorporating customers demands and quality issues. QFD has been successfully used by many major corporations, including John Deere, Ford, Chrysler, General Motors, Boeing and Hewlett Packard (Bahill and Chapman, 1993: 24).

Purpose

This study attempts to look at QFD from the OR analyst's perspective, comparing QFD to operations analysis standards. Where discrepancies appear, the problems are analyzed and solutions are proposed. Of special concern is how ACC uses QFD for the MPP. ACC digresses from the traditional use of QFD for manufacturing processes to use it as a planning tool. The goal is to incorporate the demands of the Air Force mission into the modernization planning effort. The framework for ACC's interpretation of QFD is the STT hierarchy pictured in Figure 2. ACC's use of QFD

to identify and quantify current deficiencies and quantify the value of alternative future solutions has led to the investigation of problems with QFD, both generally and with how ACC employs it.

Methodology

The methodology of this work will examine the inconsistencies found with QFD and propose near-term and far-term solutions. Among the issues to be discussed are measurement theory, mathematical programming and multi-attribute value theory (MAVT). Measurement theory is important because the scale of the numbers used in QFD dictates what numerical transformations are possible and what the final numbers of QFD signify. ACC would like to take the final numbers resulting from the QFD process and use them as inputs for a capital budgeting problem. MAVT is a decision making technique widely accepted in the OR community (Kirkwood, 1997; Keeney and Raiffa, 1990; Clemen, 1996: 530-606; Hillier and Lieberman, 1990: 828-850; Winston, 1994: 771-798). Comparing QFD to MAVT may offer insight into the issues encountered with QFD as well as provide ideas for solutions.

Chapter 2

LITERATURE REVIEW

Quality Function Deployment

Quality function deployment is a loose translation of the Japanese phrase *HinShitsu KiNo TenKai*; the word *HinShitsu* can be translated as qualities or characteristics, *KiNo* as function or method, and *TenKai* as deployment (Bahill and Chapman, 1993: 33). Unfortunately, the translation loses some of the meaning; the Japanese words have a broader meaning which describe the process. "Quality function deployment means that responsibility for producing a quality item must be assigned to all parts of a corporation" (Akao and Kogure, 1983: 26). A better interpretation of QFD might be a "customer-driven planning process." There have been numerous books and articles written about QFD. Many of these sources praise its possibilities and uses in a wide spectrum of disciplines (Akao, 1990; Day, 1993; Sullivan, 1988). Unfortunately, QFD has been generalized so much that it can be taken and molded into any process the user wishes whether it is theoretically suited to the true process or not. Otherwise, the literature only shows how QFD can be applied to a specific case. While the case studies are helpful, they do not delve into the theory that produces and supports the use of QFD or the underlying assumptions necessary to implement QFD. Assumptions are rarely mentioned. It is difficult to know if they were even considered by many of its adopters. This could result in the process of QFD being permutated from its original form. If this occurs, the outcome can be meaningless. Furthermore, many of the case studies only make use of the

initial QFD matrix, the House of Quality (HOQ), which compares customer attributes to engineering characteristics (Cohen, 1988; De Vera et al., 1988; Hauser and Clausing, 1988; Mallon, and Mulligan, 1993).

"The House of Quality" by Hauser and Clausing (1988), explains how the house of quality in QFD offers a conceptual map for planning and communications both within and across functional areas (Hauser and Clausing, 1988: 63). This article, frequently referenced in QFD literature, offers a baseline or starting point for QFD as used in the US.

The main case study referenced in this investigation of QFD is Bahill and Chapman's "A Tutorial on Quality Function Deployment" (Bahill and Chapman, 1993). This article develops and walks through the entire QFD process for a new product. It is an excellent example because instead of stopping after only one house of quality, like the vast majority of the case studies published, it follows the process through four houses. This example has been adapted for illustrative use later.

Background

QFD is a customer driven process that converts the customers' demands into quality characteristics of a product and further, into technical requirements and actions. One of the main incentives behind the use of QFD is that it helps significantly in reducing new product development time by addressing customer concerns up front. QFD is also valuable in determining and prioritizing critical items where quality technology and engineering effort should be applied (Fortuna, 1988: 24). It aids in identifying conflicting design requirements and tradeoffs and works as a planning mechanism.

The most commonly used aspect of QFD in the United States is the house of quality. This is the first step in the process; it relates the original customer demands (or objectives to be accomplished), the "*Whats*," to engineering characteristics (the means to accomplish the objectives), the "*Hows*." The relationship matrix shows the correlation between the two. The "roof" of the house is the tradeoff matrix, which is critical in helping engineers balance design characteristics (Hauser and Clausing, 1988: 67). Building the house is a relatively straightforward process; the difficulty is learning to think in terms of QFD's conventions. Evans and Lindsay go through the process of building the house in six basic steps.

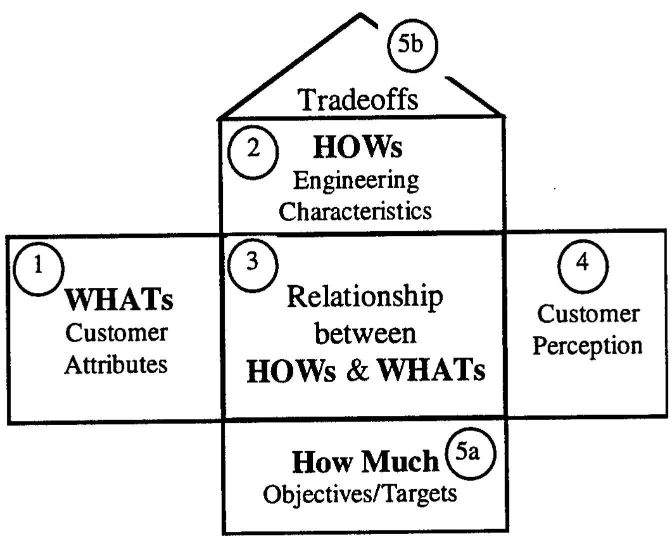


Figure 3: The House of Quality (Delano, 1997: 3)

1) Identify customer demands (*Whats*) and assign weights based on customer surveys, focus groups, marketing research, etc. "Weightings are displayed in the house next to each CA [customer attribute or demand] – usually in terms of percentages, a complete list totaling 100%" (Hauser and Clausing, 1988: 66).

2) Identify engineering characteristics (*Hows*) by asking, "*How* can we measure *what* the customer wants?" The engineering characteristics should be in measurable terms that directly affect customer perceptions (Hauser and Clausing, 1988: 66).

3) Relate the customer attributes to the engineering characteristics. Most teachers of QFD recommend using symbols for relationships, a double circle, ◎, for a strong relationship, a single circle, O, for a moderate relationship, and a triangle, Δ, for a weak relationship (Day, 1993: 71). The corresponding numbers are substituted in later because symbols are easier to read and "tend to quickly telegraph the ideas of strong, moderate, or weak relationships" (Day, 1993: 71). The use of color is also helpful in reading quality charts. The most common scoring method used is the 9-3-1 weighting (Day, 1993: 93).

◎ 9 - high correlation

O 3 - moderate correlation

Δ 1 - weak correlation

blank – no correlation

"The concept is that a weight can be calculated for each column that represents a combination of both the customers' level of importance and the strength of the relationships" (Day, 1993: 93). This provides an idea of the strength of the relationships (or the degree of correlation) between the *Whats* and the *Hows*. If any row is blank, customer demand is not completely satisfied; the engineering characteristics should be reevaluated, possibly adding one or more characteristics. The customer demand may be deleted or rolled into another characteristic. If this

happens, however, it should be well documented to prove that the customer demands were considered (Bahill and Chapman, 1993: 26).

4) Conduct an evaluation of competing products. "Companies that want to match or exceed their competition must first know where they stand relative to it" (Hauser and Clausing, 1988: 66). Comparison with the competition may also identify opportunities for improvement (66). This stage is also where alternatives are evaluated.

5) Evaluate engineering characteristics

   a. Develop objectives/targets. To find the total for each engineering characteristic, multiply each cell's value by the weight of the corresponding customer demand and sum the column. In Akao's text on QFD in Japan, he discusses evaluating the importance of a counterpart characteristic:

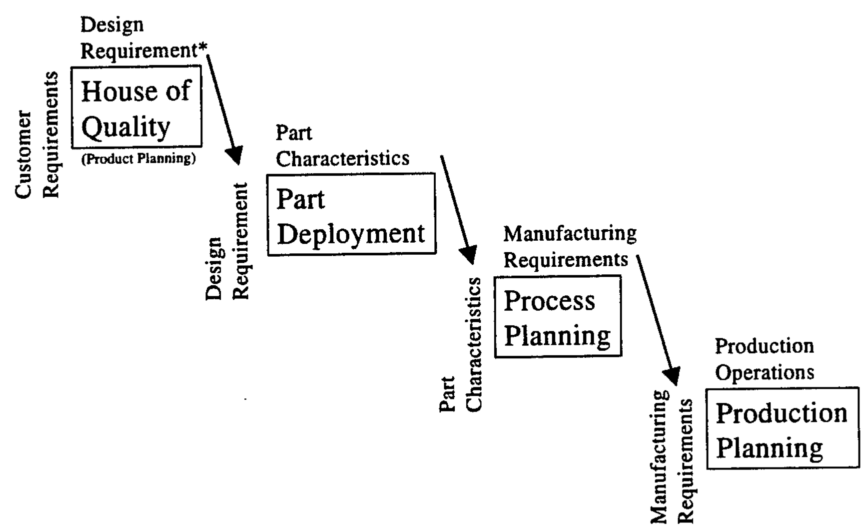
   > The QFD user can determine which quality characteristics to explore by converting the importance of demanded quality items [Customer Attributes] into the importance of counterpart characteristics [Engineering Characteristics]. This conversion of degree of importance into importance of counterpart quality characteristics can be expressed by the following equation:
   >
   > $$W_j = \sum X_i a_{ij}$$
   >
   > where: X_i = the evaluation score of the demanded quality to be correlated
   >
   > a_{ij} = the strength of the match (Akao,1990: 60)

   b. Determine tradeoffs in the "roof" (see 5b, Figure 3). The top triangle shows interrelationships between the *Hows*. The correlations in the roof

alert the system engineers/designers to interactions that have different consequences (Bahill and Chapman, 1993: 27).

6) Determine which engineering characteristics to deploy in the remainder of the production process. This aids in highlighting the user's competencies and strengths.

It is common (especially in the US) to stop after the initial matrix (Cohen, 1988; De Vera et al., 1988; Hauser and Clausing, 1988; Mallon, and Mulligan, 1993). However, one of the key benefits of QFD is its traceability through the entire design cycle. The house of quality can be linked to the next step. As shown in Figure 4, the *Hows* in the first house become the *Whats* in the next house.



*Design Requirements are interchangeable with Engineering Characteristics.

Figure 4: Linking the Houses (King, 1989: 2)

There are many software packages tailored specifically for designing QFD matrices. However, the math involved in QFD is simple enough that any standard spreadsheet program may be used to design and link the HOQs. For the examples in later chapters, Excel workbooks were used (see also Appendix A). It is important to maintain that the

actual QFD chart is not the main objective; indeed, a primary benefit of QFD is the process of making the chart (Day, 1993: 196).

The Mathematics of QFD

The mathematics involved in QFD, within one HOQ, as well as linking houses is straightforward. Figure 5 uses a truncated version of the ToothBrite example in the 1993 Bahill and Chapman article to illustrate how the original scores are used to find the scores for the objectives/target block in the bottom of each HOQ. If a process runs through all four HOQs, the final score is a function of the scores in all the previous HOQs.

$$\text{Final score in the 4}^{\text{th}}\text{ House of Quality} = \sum_{n=1}^{e}\left[\sum_{k=1}^{d}\left[\sum_{j=1}^{b}\left[\sum_{i=1}^{a} c_i m_{ij}^{(1)}\right] m_{jk}^{(2)}\right] m_{kn}^{(3)}\right] m_{n1}^{(4)}$$

where, c_i = importance score for customer demand i

$m_{ij}^{(p)}$= HOQ #p relationship value (9-3-1-0) for row i, column j

This score is then used as an indicator of which aspects of the process the company should concentrate on to incorporate quality into the entire process. "The end result is that the information in the manufacturing area stems from the knowledge of the customer" (Day, 1993: 165). Because everything is linked back to customer demands, the QFD process captures the "voice of the customer" early on in the design process. Remember, the matrices themselves are not the goal of QFD, rather it is the process of building HOQs and the information that comes from that process that provides the most benefit to QFD users.

Customer Demands v. Quality Characteristics	Importance (1to 10)	Pleasing Appearance	Cost to Produce
c_1 Hygienic	7		9
c_2 Reasonable Cost	9	1	3
Score		9	90
Rank		2	1

$m_{ij}^{(1)}$

$$\sum c_i m_{i1}^{(1)}$$

Quality Characteristics v. Product Characteristics	Weights	Size of Container	Shape of Container
Pleasing Appearance	9	3	3
Cost to Produce	90	3	9
Score		297	837
Rank		2	1

$m_{jk}^{(2)}$

$$\sum_{j=1}^{b}\left[\sum_{i=1}^{a} c_i m_{i1}^{(1)}\right] m_{j1}^{(2)}$$

Product Characteristics v. Manufacturing Processes	Weights	Create Mold	Blow Material	Insert and Bond Liner
Size of Container	297	9		1
Shape of Container	837	9	9	3
Score		10206	7533	2808
Rank		1	2	3

$m_{kn}^{(3)}$

$$\sum_{k=1}^{d}\left[\sum_{j=1}^{b}\left[\sum_{i=1}^{a} c_i m_{ij}^{(1)}\right] m_{jk}^{(2)}\right] m_{k1}^{(3)}$$

Manufacturing Processes v. Quality Controls	Weights	Mold Dimensions	*Material Controls*	Temperature	*Welding Controls*	Intensity	Cleanliness and Hygine Controls
Create Mold	10206	9					1
Blow Material	7533			9			
Insert and Bond Liner	2808	1				1	
Score		94662		67797		2808	10206
Rank		1		2		4	3

$m_{nm}^{(4)}$ *(scores)*

$$\sum_{n=1}^{e}\left[\sum_{k=1}^{d}\left[\sum_{j=1}^{b}\left[\sum_{i=1}^{a} c_i m_{ij}^{(1)}\right] m_{jk}^{(2)}\right] m_{kn}^{(3)}\right] m_{n1}^{(4)}$$

Figure 5: The Mathematics of QFD

QFD as a Planning Tool

QFD was originally intended for manufacturing processes, to ensure quality in new products. It "is a method for developing a design quality aimed at satisfying the consumer and then translating the consumer's demands into design targets and major quality assurance points to be used throughout the production stage" (Akao, 1990: 3). However, QFD is a flexible tool that has been adapted for other uses.

> For many organizations, it is a simple extension of this thought process to recognize the potential for QFD in nonproduct applications. They realize that customers can be internal as well as external and that the matrix can be used to organize and evaluate almost any issue. (Day, 1993: 195)

Most organizations already have an overall planning process that involves a vision of where they wish to be in the future. This can be translated into a set of objectives. "At subsequent levels, the organization can develop strategies and action plans" (Day, 1993: 196). The first HOQ then would have vision statements as the *Whats* on the left side to represent the "voice of the organization" with objectives across the top as the *Hows*. In this matrix, each column (objective) should have at least one strong relationship to a vision statement or it should be reexamined. It may be too broad, too weak, or belong at a lower level (Day, 1993: 198). The next matrix in the planning process would be the objectives versus strategies, which represent how the objectives will be answered. Again, each column should score at least one strong relationship; each objective should have a strong strategy or set of strategies for its accomplishment (Day, 1993: 198).

The next level has strategies on the left and action plans across the top that represent how the strategies will be accomplished. This is the lowest level of Day's breakout of the planning process, but it is not a rigid rule. The process should be broken down until it

reaches a measurable level (Day, 1993; 200). When using QFD for planning, all items are transferred to the next level, not just the high priority items. "At each stage of the business planning process, the input to the matrix is translated into a greater level of actionable detail" (Day, 1993: 202).

QFD is valuable as a planning system because it is customer focused and it helps organizations investigate all aspects of their operations including inputs, outputs, and the strength of relationships in the HOQ. In each subsequent house, the level of specificity increases; the items at the lowest level represent actions that must be completed to accomplish the initial inputs (for ACC, the campaign objectives). It is important to remember the goal behind developing a QFD matrix is not the matrix itself, but to help the users organize their thought processes, "explore various ways to develop strong outputs for each of the inputs, and strengthen the plan where weaknesses are observed" (Day, 1993: 218).

Measurement Theory

Measurement is the process of assigning numbers or other symbols to things so that properties of the numbers or symbols represent properties of the thing being measured. A scale of measurement is a particular way of assigning numbers of symbols (Krantz, 1998: 2). Measurement theory is what allows assumptions to be made as well as transformations to be performed on numbers. When measurement is thought of, it is usually along scientific terms, of physical attributes such as length, weight or temperature; however, the rules still apply when measuring preference and importance.

There are two ideas that provide the foundations for measurement: representation and uniqueness. Representation concerns the "justification of the assignment of numbers to objects or phenomena" (Suppes and Zinnes, 1963: 4). "A representation theorem asserts that if a given relational structure satisfies certain axioms, then a homomorphism into certain numerical relational structure can be constructed" (Krantz et al., 1971: 9). Representation allows scales to be created. Uniqueness concerns the specification of the degree to which the assignment made possible by the representation theorem is unique (Suppes and Zinnes, 1963: 4). Uniqueness deals with the scale of measurement, it involves defining what kinds of transformations are permissible. "The number assigned to measure mass is unique once a unit has been chosen...the measurement of mass is unique up to a similarity transformation [$\phi(x) = \alpha x$, $\alpha > 0$]," (Suppes, 1959: 131). For example, an object's mass may be measured in grams or pounds the difference being a multiplicative factor of 453.6. However the mass of the object is the same regardless of the units used (a 1 pound object has the same mass as a 453.6 gram object). Distance is a similar sort of measurement. "The ratio of the distance between Palo Alto and San Francisco to the distance between Washington and New York is the same whether the measurement is made in miles or yards" (Suppes and Zinnes, 1963: 9).

The main issue in measurement theory of concern here, is meaningfulness. It involves how measurements are used. "A numerical statement is *meaningful* if and only if its truth (or falsity) is constant under admissible scale transformations of any of its numerical assignments, that is, any of its numerical functions expressing the results of measurement" (Suppes and Zinnes, 1963: 66). Below the five most common scales are

defined along with a discussion of the transformations that are permissible for maintaining the same scale.

Absolute Scale

"The simplest example of a scale is where the only admissible transformation is $\phi(x) = x$. There is only one way to measure things in this situation. Such a scale is called *absolute*" (Roberts, 1979: 64). "Counting is an example of an absolute scale. The number of members of a given collection of objects is given uniquely. There is no arbitrary choice of unit or zero available" (Suppes and Zinnes, 1963: 9).

Ratio Scale

> Suppose the admissible transformations are all functions ϕ: f (A)$\rightarrow$B of the form $\phi(x) = \alpha x$, $\alpha > 0$. Such a function ϕ is called a *similarity transformation*, and a scale with the similarity transformations as its class of admissible transformations is called a *ratio scale*. Mass defines a ratio scale, as we can fix a zero point and then change the unit of mass by multiplying by a positive constant. Thus, for example, we change from grams to kilograms by multiplying by 1000. The term ratio scale arose because ratios of quantities on a ratio scale – for example, mass – make sense. (Roberts, 1979: 64-65)

"The term 'ratio scale' comes from the fact that if $\phi \rightarrow \alpha\phi$ are the only permissible transformations, then the ratios of scale values are determined uniquely (Krantz et al., 1971: 10)." The ratio scale has a natural zero that exists "when there is a satisfactory answer to the question: Is there a real meaning to having nothing or none of the quantity being measured" (Miller and Starr, 1967: 92).

Interval Scale

The difference between the ratio scale and the interval scale is that there is one "free" choice for the ratio scale and two "free" choices for the interval scale (Miller and Starr,

1967: 91). In the ratio scale the free choice corresponds to the α in $\phi(x) = \alpha x$ and in the interval scale the free choices correspond to the α and β in $\phi(x) = \alpha x + \beta$ (Miller and Starr, 1967: 92). Varying the zero point and the unit leads to *affine* transformations of the form $\phi \rightarrow \alpha\phi + \beta$, $\alpha > 0$. The scale whose permissible transformations are of this form is called the interval scale because ratios of intervals are invariant (Krantz et al., 1971: 10). These transformations, $\phi(x) = \alpha x + \beta$, $\alpha > 0$, are also known as positive linear transformations (Roberts, 1979: 65). For this scale to apply a zero (an origin) must exist to anchor the scale in order to give the score meaning.

Ordinal Scale

Monotonic increasing transformations, $\phi \rightarrow f(\phi)$, where f is any strictly increasing real-valued function, are the permissible transformations for the ordinal scale. It is called that because only the order is preserved under these transformations (Krantz et al., 1971: 11).

Nominal Scale

According to Roberts, a nominal scale is one in which all one-to-one functions ϕ define admissible transformations. "The actual number has no significance, and any change of numbers will contain the same information: identification of the elements of set *A*" (Roberts, 1979: 66).

Table 1: Scales - in order of strength

Scale	Transformation	Example
Absolute	$\phi(x) = x$ (identity)	Counting
Ratio (the unit of measurement is arbitrary)	$\phi(x) = \alpha x, \alpha > 0$ Similarity transformation	Mass Temperature in Kelvin Time (intervals) Loudness (sones)
Interval (the unit of measurement and the origin are arbitrary)	$\phi(x) = \alpha x + \beta, \alpha > 0$ Positive linear transformation	Temperature (Fahrenheit, centigrade) Time (calendar) Intelligence tests (standard scores)
Difference	$\phi(x) = x + \beta$	Thurstone Case V (measure of response strength) Logarithmic transformations of ratio scales
Log-interval	$\phi(x) = \alpha x^{\beta},\ \alpha, \beta > 0$	Psychophysical functions (e.g. loudness of a sound) Exponential transformations of interval scales
Ordinal	$x \geq y$ iff $\phi(x) \geq \phi(y)$ (strictly) monotone increasing transformation	Preference Hardness Air quality Grades of leather, wool, etc. Intelligence tests (raw scores)
Nominal	any one-to-one ϕ	Number uniforms Curricular codes

(Roberts 1979: 64-66)

Mathematical Programming

Linear programming is a subset of mathematical programming which is applicable in a variety of disciplines, a main advantage being its ability to take a verbal problem and describe it in a concise and comprehensible manner (Hillier and Lieberman, 1990: 19). It is useful because it helps to link complex problems with indistinct solutions to mathematical techniques and ultimately to computer programs.

Linear Programming

"Linear programming is a tool for solving optimization problems" (Winston, 1994: 49). The most common application is the allocation of scarce resources among competing activities (Hillier and Lieberman, 1990: 29). There are many other subsets of mathematical programming. Two of interest are, integer programming and goal programming. However, first it is important to address the assumptions required in linear programming. It is called *linear* programming for a reason; the function of interest must be linear. That is: "a function $f(x_1, x_2, \ldots, x_n)$ of $x_1, x_2, \ldots, x_n$ is a linear function if and only if for some set of constants $c_1, c_2, \ldots, c_n$, $f(x_1, x_2, \ldots, x_n) = c_1x_1 + c_2x_2 + \ldots + c_nx_n$" (Winston, 1994: 53). A linear programming problem is an optimization problem which involves taking a linear function and attempting to maximize (or minimize) it while satisfying a set of linear constraints (Winston, 1994: 53). The primary assumptions that *must* be made in linear programming are proportionality and additivity.

- **Proportionality** – "the contribution of the objective function from each decision variable[1] is proportional to the value of the decision variable" (Winston, 1994: 53). When this assumption does not hold, it usually means other methods such as nonlinear programming are necessary to solve the problem.
- **Additivity** – "the contribution to the objective function for any variable is independent of the values of the other decision variables" (Winston 1994: 53). Additivity ensures none of the variables are double counted.
- **Divisibility** – assumes that each decision variable can take on fractional values (Winston 1994: 54).
- **Certainty** – assumes that each parameter (the coefficients) is known with certainty (Winston, 1994: 54).

[1] Decision variables make up the objective function and should completely describe the decisions to be made.

Integer Programming

An integer programming problem is a specialized form of a mathematical programming problem. In a pure integer programming problem, all variables are required to be integers. "This is actually equivalent to assuming the data rational, since multiplication of the objective function by any positive number, or any constrain by any nonzero number, does not change the problem" (Garfinkel and Nemhauser, 1972: 5). Integer programming is required when it does not make sense to have fractional values, for example 1.5 people cannot be allocated to a project and defense contractors might be upset if the Air Force were to buy only half of an F-15. Integer programming is vital because it removes the divisibility assumption required in a standard linear programming problem.

Goal Programming

Goal programming is an important tool when there are competing objectives (e.g. lives vs. money, range vs. speed, distance vs. accuracy). Goal programming establishes a specific numeric goal for each objective and subsequently seeks a solution that minimizes the deviations from the goal (Hillier and Lieberman, 1990: 271). There are two types, preemptive and nonpreemptive. In nonpreemptive goal programming, all of the goals are considered to have roughly the same relative importance; however, the penalty for missing each goal may be different. For example, management may consider overshooting an employment goal per unit to be half as serious as undershooting a profit goal (Hillier and Lieberman, 1990: 273). The objective function in nonpreemptive goal programs optimizes the amount by which the goal is numerically under or over exceeded, using deviational variables. The weight associated with the deviational values for each goal is the coefficient in the objective function. In preemptive goal programming, the

goals are prioritized. This usually applies when one or more of the goals clearly is considerably more important than the others (Hillier and Lieberman, 1990: 274). "To apply preemptive goal programming the decision maker must rank his or her goals from the most important (goal 1) to least important (goal *n*). The objective function coefficient for the variable representing goal *i* will be P_i" (Winston, 1994: 778). It is assumed that $P_1 >>> P_2 >>> P_3 >>> \cdots >>> P_n$. Goal programming can be useful in decision analysis because it deals with multi-attribute decision making. Common objective functions for goal programming problems are usually either an additive value function where there exist *n* functions $v_1(x_1), v_2(x_2), \ldots, v_n(x_n)$ satisfying $v(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} v_i(x_i)$, and the purpose is to maximize value or an additive cost function of the same form with the objective of minimizing cost (Winston, 1994: 772). Several essential conditions must be met for the additive value function to apply. For one, mutual preferential independence is required. Preferential independence means that the values of one attribute do not depend upon the values of any other attributes (Winston, 1994: 773). Mutual preferential independence implies that attribute *a* is preferentially independent of attribute *b*, and attribute *b* is preferentially independent of attribute *a* (Winston, 1994: 773). This leads to an important theorem:

Theorem: Given attributes $X_1, \ldots, X_n$, $n \geq 3$, an additive value function

$$v(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} v_i(x_i)$$

(where v_i is a value function over X_i) exists if and only if the attributes are mutually preferential independent. (Keeney and Raiffa, 1993: 111).

Proof: See Keeney and Raiffa.

Goal programming, with linear programming (given each v_i is also linear), uses an additive objective function in the form described above to determine the optimal decision (Winston, 1994: 775).

Capital Budgeting Problems

Capital budgeting problems are very common mixed integer programming applications to determine optimal financial decisions (Winston, 1994: p.77). These models are extremely useful when limited investment funds (resources) must be allocated to investment projects and the decision is which projects to select. In real world applications, these problems often become quite large and traditional methods for finding an exact solutions are computationally challenging. In these cases, it is often best to resort to a heuristic approach to find an approximation in a more efficient manner.

Multi-Attribute Value Theory

Decision analysis is the science of applying mathematical theory to complex, sometimes uncertain decision situations. Decision analysis provides an overall paradigm and a set of tools with which a decision maker can construct and analyze a model of the decision situation. It helps to represent real world problems using models that can be analyzed to gain insight and understanding (Clemen, 1996: xix).

Utility theory is used in decision analysis to deal with uncertain environments. It was developed by von Neumann and Morganstern almost accidentally in their research into gaming (a highly uncertain environment) (von Neumann and Morganstern, 1947). A significant dilemma is how to describe the fundamental concept of individual preference using utility. Utility was first conceived as quantitatively measurable (a number). It is

based on the immediate sensation of preference of one/many object(s) against another (von Neumann and Morganstern, 1947: 16). A critical assumption of utility theory is that imagined events can be combined with probabilities and therefore the same may be assumed for the utilities attached to them (von Neumann and Morganstern, 1947: 20).

The published decision analysis studies go into great depth and are excellent illustrations of the process. Two of the most notable names associated with decision analysis, more specifically, value focused thinking and multi-attribute utility theory (MAUT), are Ralph Keeney and Howard Raiffa. Their text, Decisions with Multiple Objectives (1976), offers a comprehensive look into both multi-attribute value and utility theory with the mathematics that back the theory up as well as a number of case studies. This text, along with Keeney's Value Focused Thinking (1992), helps not only to analyze decision situations, but also to build the objectives and structure of the problem to ensure the correct issues are carefully and completely addressed. The structure and initial steps for analyzing a decision situation are the same whether using value, which is deterministic, or utility, which involves uncertainty.

A decision problem using MAVT needs to be properly designed before it is analyzed. Perfect analysis of the wrong problem is worth no more than bad analysis on the right problem. Proper structuring of the objectives results in a deeper/more accurate understanding of what one should care about in the decision context. Problem structuring helps clarify the decision context, define fundamental objectives and provide the basis for the use of quantitative modeling (Keeney, 1992: 69). Fundamental objectives are defined as the objectives that reflect what really needs to be accomplished (Clemen, 1996: 44).

The objectives should be as useful as possible for creating and evaluating alternatives, identifying decision opportunities and guiding the entire decision making process. A hierarchy is an excellent way to structure fundamental objectives to help simplify a complex decision situation. Means objectives are defined as the objectives that are important because they help achieve other objectives (Clemen, 1996: 44). The means objectives offer guidance about the decision situation, are the means to the achievement of fundamental objectives, and are useful for creating alternatives (Keeney, 1992: 34-35). The means objectives are best organized as a network. The overall objective for a decision situation defines the breadth of concern and is the same for means-end and fundamental objective structures. However to some degree, all of the means objectives are means to all of the fundamental objectives. The fundamental and means objectives may be separated by the reason they are on the list (of objectives) for the decision situation. Additionally, tracing ends objectives for specific means objectives should lead to at least one fundamental objective. The lowest level objectives are divided into attributes or measures, which are characteristics of desirable solutions.

Desirable Properties of Attributes in MAVT (Keeney and Raiffa, 1993: 50-52):

1. Complete (collectively exhaustive) – This is required to ensure all important aspects of the problem are covered. It is met if the set of attributes adequately indicates the degree to which the overall objective of the decision situation is met.
2. Operational – Attributes need to be meaningfully used in analysis as well as useful in helping the decision maker choose the best course of action.

3. Decomposable – Aspects of the evaluation process need to be able to be simplified by breaking attributes into parts.
4. Nonredundant (mutually exclusive) - Avoid double counting. This is related to the additivity assumption in linear programming.
5. Minimal – Keep the set of attributes small to keep the problem dimension as small as possible.

It is important to ensure these properties are met by the attributes; without these, the assumptions for the decision analysis fall apart. Once a hierarchy is built to the satisfaction of the decision maker, the five steps listed below can be implemented. All MAVT procedures include these five steps (Von Winterfeldt and Edwards, 1986: 273).

1. Define alternatives and value-relevant attributes.
2. Evaluate each alternative separately on each attribute.
3. Assign relative weights to the attributes.
4. Aggregate the weights of attributes and the single-attribute evaluations of alternatives to obtain an overall evaluation of alternatives.
5. Perform sensitivity analyses and make recommendations.

Depending on the source, these five steps may be carried out in very different manners. However, each method strives towards the same result, to help the analyst guide the decision maker in choosing the best decision based on his values and current information. ACC currently uses QFD to help prioritize the alternatives (solutions) for the MPP. MAVT is an alternative method which may be viable.

Chapter 3

ANALYSIS OF QFD

In any mathematical procedure, there are initial assumptions (or given statements) to help set the boundaries of the process and drive the inputs. The assumptions of QFD are analyzed, specifically the assumptions that are made when using QFD for evaluating alternatives in a multi-objective situation. One such assumption of QFD is the scale of the numbers used. After establishing the assumptions, the analysis will explore potential problems that could be encountered using QFD. Investigating the similarities between QFD and MAVT may offer further insight into QFD. A set of solutions is proposed to combat the issues faced in implementing QFD. Finally, a set of recommended rules is presented to offer both current and future users of QFD some guidelines.

QFD Advantages

QFD has many proponents, primarily in management, who tout its benefits. It has been supported in a variety of journals by professionals who have successfully applied QFD. The list includes, Yoji Akao, one of the founding fathers of QFD in Japan at the Kobe Shipyard, Robert King, author of Better Designs in Half the Time, James L. Bossert, author of Quality Function Deployment, Ronald M. Fortuna, and Andrew E. Kenny. These sources list numerous advantages to using QFD. The following is a compilation of the major benefits of QFD.

QFD is good for organizing thoughts and identifying needs and competencies. This helps increase customer satisfaction and market share (Fortuna, 1988: 24) because the QFD process forces management to address customers' demands and helps organizations ensure the demand is satisfied. QFD also helps companies use competitive information more effectively and prioritizes the results (Bossert, 1991: 6). If enough work is done initially to organize and research the inputs to QFD, it will also help identify missing assumptions (Bossert, 1991: 6). Naturally, along with improving quality, the purpose behind QFD is to reduce costs and a major benefit is that start-up costs are minimized (Kenny, 1988: 30).

Using QFD can reduce implementation time, in some cases, its use has been known to cut the design cycle in half (Kenny, 1988: 30). This limits post-introduction problems because it deals with them up front, and it avoids future development redundancies (Bossert, 1991: 6). With more thought put into the initial development, engineering changes can be reduced by two-thirds (Kenny, 1988: 30).

QFD promotes teamwork because it is consensus based. The collaboration required by QFD also serves to create communication and identify actions at interfaces. This in turn helps create a global view out of the details (Bossert, 1991: 6). Teamwork leads to QFD improved designs and performance (Fortuna, 1988: 24). Engineering changes after start-up are virtually eliminated (Kenny, 1988: 30). Furthermore, QFD also identifies future application opportunities or alternatives (Bossert, 1991: 6).

Another important aspect of QFD is that it provides documentation. It documents the rationale for design, adds structure to the information, and adapts to changes; it is a living

document (Bossert, 1991: 6). QFD is especially useful for conveying engineering knowledge and experience from generation to generation (Fortuna, 1988: 24). This is a particularly valuable characteristic for military organizations because of the frequent turnovers of personnel.

QFD Disadvantages

Despite the myriad of advantages listed above, QFD is not a panacea for planning and manufacturing processes. It is a flexible tool that, like any new process, can be applied incorrectly or inconsistently. Furthermore, if applied incorrectly, QFD may increase the workload and without producing the advertised benefits of reducing time and problems in production development and increasing customer satisfaction and sales (Akao, 1990: 3). King mentions a few common disadvantages (King, 1987: 279-280).

1. The quality charts get too big.
2. Demanded quality is too difficult to learn.
3. Some answers are too difficult to categorize as demanded quality.
4. Determining the degree of interrelationships between customer demands and quality characteristics can be very difficult.
5. Users can not judge the appropriateness of some demanded quality items.

King does not explicitly define demanded quality in his article. However, he references Akao who combined a series of articles by Japanese authors introducing and explaining QFD. Demanded quality is what the customer demands; it refers to capturing the "voice of the customer". These are broken out into levels to add detail where appropriate (Akao, 1990: 18). Dealing with demanded quality is the reason QFD exists. Unfortunately, King

asserts this is where users have the most problems with QFD. Until QFD users understand their customers, they will continue to have difficulty with demanded quality.

QFD does not explicitly take into consideration the ranges when assessing the weights of attributes (Delano, 1997: 38). In MAVT, this is a crucial aspect of building the decision context. Swing weights are used to assess the range of attributes. That is, the decision-maker partakes in a thought experiment where he/she compares individual attributes directly by imagining hypothetical outcomes (Clemen, 1996: 547). Swing weights are scaling constants used to help make the analysis more meaningful. When using a constructed scale, there are usually no meaningful numerical measurements attached to specific levels in that scale. A constructed scale is a user-defined scale developed for a particular decision problem for measuring the degree of achievement of an objective (Kirkwood, 1997: 24). The decision maker must rate the different levels of the scale to indicate how much each level is worth relative to the other levels (Clemen, 1996: 130). The advantage of swing weights is they are sensitive to the entire range of possible attribute values.

Another drawback to QFD is there is no way to incorporate risk or uncertainty into the process. Utility theory however, was designed specifically to handle uncertainty. "Decision analysis incorporates uncertainty through probabilistic analysis and assesses risk preferences via utility functions; however the QFD process provides no means to incorporate these concepts" (Delano, 1997: 34). This is probably the primary discrepancy between QFD and decision analysis.

When QFD is used as a planning tool, as ACC does, there is also the problem of the restricted levels of the matrices, this prohibits customer attributes or engineering characteristics from being further explored. This inflexibility is attributed to the fact that when using QFD for planning, *all* items are transferred to the next level, not just the high priority items (Day, 1993: 202). The final level may be too specific for some attributes and too broad for others. There is no flexibility in building the QFD structure for planning – all attributes are broken to the same level. If a QFD level is too specific, the attributes are broken apart into meaningless categories.

Assumptions

Once the customer demands are identified and assigned importance scores, the appropriate engineering characteristics are generated. The next step is to quantify the relationship between the customer demands and engineering characteristics. The importance scores and the matrix relationships heavily influence the resulting rankings in the bottom block of the HOQ. One initial assumption made is that the list of customer demands is collectively exhaustive. This is not critical for using QFD but if customer demands are missing, the QFD process could fail to capture what is really important to the customer. Moreover, to be able to perform computations or make conclusions based on the numbers used in QFD it is important to know what assumptions are being made about the inputs to the process. In order to make comparisons between the customer demand importance scores and mathematical transformations to be performed upon them, the scale of the scores must be known.

The Scale for QFD

The importance of establishing the correct scale is to reinforce the theory behind the mathematics and computations involved in QFD. It is also essential to ensure that users understand *what* QFD is measuring. This should aid in identifying the most appropriate scale. "The major source of difficulty in proving an adequate theory of measurement is to construct relations which have an exact and reasonable numerical interpretation and yet also have a technically practical empirical interpretation" (Scott and Suppes, 1958: 113). Knowing the scale is critical to knowing if a number is meaningful. "An empirical hypothesis, or any statement in fact, which uses numerical quantities is empirically meaningful only if its truth value is invariant under the appropriate transformations of the numerical quantities involved" (Suppes, 1959: 131). Meaningful statements are unambiguous and say something significant about the relationships among the characteristics being measured, "whereas statements that are dependent on a particular, arbitrary choice of scale do not" (Roberts, 1979: 58). In order for the QFD scores that come from any given house or matrix to be used in any mathematical computations including being carried over as weights to the next HOQ or in mathematical programming, the scores must be meaningful. In QFD, the scale is not securely anchored. This means there is no set origin. What does a 9, 3, or 1 actually mean? Unless care is taken in asking explicit questions and defining the scale in use, these numbers have no consistent meaning and performing operations on them is meaningless. The HOQ pictured below (Figure 6) reviews the components of one level of QFD.

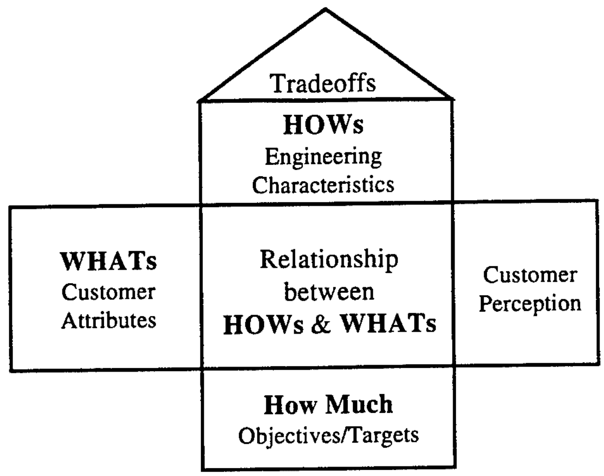


Figure 6: The House of Quality (Delano, 1997: 3)

Inside the HOQ, the importance of the relationship between the customer attributes and the engineering characteristics is quantified. The standard QFD scoring system is:

9 - strong correlation (◎)

3 - moderate correlation (○)

1 - weak correlation (Δ)

0 - no correlation (blank)

Depending on the user, a strong correlation may correspond to a 5. This value is frequently used in Japan (Akao, 1990: 70), although the 9-3-1 system is the most common in use in the US (Day, 1993: 93). The question of interest here is: what scale applies for each part of the HOQ, the importance scores for the customer demands, the scoring system inside the relationship matrix and the final scores at the bottom of the house.

Since QFD treats the customer demand importance scores as weights, they are assumed to be on a ratio scale. This means if customer demand X scores a four and another customer demand, Y, receives a two, then X is twice as important to the customer as Y

(i.e. a gain of 1 point in X is equal to a gain of 2 points in Y). According to Akao, no theoretical basis has been formulated for evaluating the customer demand importance weights (Akao, 1990: 29). To give QFD users the benefit of the doubt, the initial assumption that the customer demand scores are on a ratio scale is made. Miller states that, weights should be "interpreted as an indication of the perceived relative importance of satisfying that subcriterion" (J. R. Miller, 1970: 46). Miller's subcriterion corresponds to customer demands in QFD. Relative importance means relative to the other customer demands and it "will be reflected in the *ratios* of any two weights assigned, respectively, to two separate subcriteria [customer demands] in a given set" (J. R. Miller, 1970: 46). Thus, it is advantageous to assume the customer demands are on a ratio scale. However, weights may lose their importance or be overstated when the range of the customer demands is inconsistent. "Wide differences in relative interpretive quality could seriously distort a decision" (J. R. Miller, 1970: 47). It is conceivable that one important customer demand cannot be interpreted with any quality measures. An inability by decision makers to accurately articulate what a customer demand means could lead to artificially inflating the importance of that demand, causing it to overshadow the other demands. When evaluating the weights, care must be taken in how they are elicited from customers (in surveys, focus groups and through company research) to ensure the scores are indeed on a ratio scale.

Generalized Form of QFD

The tables on the following page show the components of two linked HOQs represented as variables along with the transformations of the scores.

Table 2: HOQ 1 – generalized

CUSTOMER DEMANDS v. ENGINEERING CHARACTERISTICS	IMPORTANCE	Engineering Characteristic 1	Engineering Characteristic 2
Customer Demand 1	c_1	$m_{11}^{(1)}$	$m_{12}^{(1)}$
Customer Demand 2	c_2	$m_{21}^{(1)}$	$m_{22}^{(1)}$
Customer Demand 3	c_3	$m_{31}^{(1)}$	$m_{32}^{(1)}$
Score		$\sum_{i=1}^{3} c_i m_{i1}^{(1)}$	$\sum_{i=1}^{3} c_i m_{i2}^{(1)}$

where,

c_i = importance score for customer demand i

$m_{ij}^{(p)}$ = HOQ $\#p$ relationship value (9,3,1,0) for row i, column j

HOQ 1 math:

$$\sum_{i=1}^{3} c_i m_{i1}^{(1)} = c_1 m_{11}^{(1)} + c_2 m_{21}^{(1)} + c_3 m_{31}^{(1)}$$

$$\sum_{i=1}^{3} c_i m_{i2}^{(1)} = c_1 m_{12}^{(1)} + c_2 m_{22}^{(1)} + c_3 m_{32}^{(1)}$$

Table 3: HOQ 2 – generalized

ENGINEERING CHARACTERISTICS v. PRODUCT CHARACTERISTICS	WEIGHT	Product Characteristic 1	Product Characteristic 2
Engineering Characteristic 1	$\sum_{i=1}^{3} c_i m_{i1}^{(1)}$	$m_{11}^{(2)}$	$m_{12}^{(2)}$
Engineering Characteristic 2	$\sum_{i=1}^{3} c_i m_{i2}^{(1)}$	$m_{21}^{(2)}$	$m_{22}^{(2)}$
Score		$\sum_{j=1}^{2}\left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{j1}^{(2)}$	$\sum_{j=1}^{2}\left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{j2}^{(2)}$

HOQ 2 math:

$$\sum_{j=1}^{2}\left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{j1}^{(2)} = \left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{11}^{(2)} + \left[\sum_{i=1}^{3} c_i m_{i2}^{(1)}\right]\cdot m_{21}^{(2)}$$

$$\sum_{j=1}^{2}\left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{j2}^{(2)} = \left[\sum_{i=1}^{3} c_i m_{i1}^{(1)}\right]\cdot m_{12}^{(2)} + \left[\sum_{i=1}^{3} c_i m_{i2}^{(1)}\right]\cdot m_{22}^{(2)}$$

The transformation pictured above would be repeated with each subsequent house, eventually resulting in the scores stated in chapter two.

Problems

1. The first issue is the question of the scale of the relationship values inside the matrix. The QFD scoring system does not allow for specificity or precision. It limits the scores to 9-3-1, or no correlation and does not allow for intermediate scores (on such a scale, an alternative cannot score a 5 or a 7). Restricting the scores could introduce bias because the discrete scores only allow for the categories of 9, 3, 1 or 0. A relationship may actually rate a 6 but with the original restricted QFD scale, receive a 9 although it is less correlated than other relationships scoring 9s. To combat the problem of the discrete scale, the scores inside the HOQ relationship matrix must be on a continuous ratio scale. With a ratio scale, the unit of measurement is arbitrary and the only admissible transformation is: $\phi(x) = \alpha x$, $\alpha > 0$. Some examples of ratio scales are mass, temperature in Kelvin, and time (intervals).
2. The scale of the final scores in a QFD matrix is also important. Using the scores out of a HOQ either as weights in another house or in a mathematical program is a serious potential source of error unless the values are on the correct scale. ACC would like to be able to take the numbers that result from the QFD process and use those scores as coefficients of decision variables in the formulation of a capital budgeting problem. ACC takes the QFD scores from the final matrix and uses them in a goal program to aid in choosing "an investment strategy from a pool of competing programs with a constrained fiscal budget that extends 25 years into the future" (HQ ACC, MIP Handbook, 1998: 7). It is theoretically unsound to use QFD values, $\left(\sum_{i=1}^{n} c_i m_{i1}^{(1)}\right)$, in mathematical programming as coefficients,

i.e. $\sum_{i=1}^{n} c_i m_{i1}^{(1)} \neq k_i$, where $z = k_1x_1 + k_2x_2 +\ldots+ k_nx_n$ and k_i are ratio based constants greater than zero, if the final values for QFD are not on a ratio scale (see assumptions in Chapter 2). The proportionality assumption of linear programming states, "the contribution of the objective function from each decision variable is proportional to the value of the decision variable" (Winston, 1994: 53). This requires a ratio scale for the decision variables and their associated constants. Furthermore, Day stresses that "the column weights that are calculated during the development of the QFD matrix *should not* be used to determine priority items. They represent an artificial number and do not consider key issues" (Day, 1993: 106). Thus, the meaningfulness of the scores at the bottom of the HOQ is questionable and using the scores for further mathematical computations could imply a precision and relationship that does not exist. It all comes down to one final question: *is there a way to make the column scores ratio*?

3. In ACC's implementation of QFD, there are inconsistencies with the scales used to score the relationships inside the QFD matrix. For the majority of the matrices, ACC uses the traditional 9-3-1 scoring system. When ACC reaches the third linked HOQ in the MPP, the operational task versus function level, the process switches to a grading scale, which is outside the scope of QFD. For this level of the matrix, ACC fills in the relationship matrix by asking the question: "How well must the CAF [Combat Air Forces] do the function to accomplish the task" (HQ ACC, MIP Handbook, 1998: A-7).

4. A specific problem of ACC's use of QFD, related to the previous problem, is that as the MPP moves through the QFD process from house to house, it changes from

correlations to performance and back to correlations. For the third linked HOQ in the MPP, the operational task versus function level, ACC is more concerned with measuring performance than with the correlation between the tasks and functions. According to Day, the horizontal elements across the top of the HOQ, the *Hows*, must be measurable (Day, 1993: 68). "One of the hardest parts of any QFD matrix development is getting people to think in global terms of measures instead of specific how-to mechanisms" (Day, 1993: 188).

5. "When determining relationship strengths, it is important to work in columns…asking 'Would we work on this technical requirement to satisfy this customer requirement'" (Day, 1993: 71). The scores between columns may not be comparable due to lack of definition in scoring values. Rules of engagement should be established by the QFD users to ensure everyone taking part in the scoring agrees on what constitutes a strong, a moderate or a weak relationship inside the matrix. Such detailed "anchoring" is a key to obtaining consistent, comparable scores. Additionally, after a matrix is filled in, a sanity check should be done for each row and column. There should be no row or column with no relationship or only weak symbols (Day, 1993: 71). Only weak scores suggest that an engineering characteristic (a *How*) has no significant relationship to the customer demand (the *What*). It is important for the people scoring to be consistent with their assessment of the scores throughout the process. The QFD scores are meaningless if a different set of people with different assumptions or definitions of the relationships score each column. For example, "cold" in Florida may not be "cold" in Alaska, just as a strong relationship to one group may not be a strong relationship to another.

6. Another drawback of ACC's use of QFD as a planning tool is that the user is restricted to the levels of the matrices and cannot delve further into a customer attribute or engineering characteristic than the lowest HOQ. This final house may be too specific for some attributes and too broad for others. There is no flexibility in building the QFD structure – it forces all attributes to be dissected to the same level of detail. If the QFD process links too many houses, attributes are broken apart into meaningless categories. If QFD stops breaking attributes apart before they are adequately defined, the score could be artificially inflated or difficult to obtain. By the time the lowest HOQ is evaluated, it could be comparing one whole system to a lug nut on another system.

The structure is a significant problem for QFD when used as a planning tool. Some actions may be simple, needing only one or two levels of detail, whereas other actions may be complicated long-term projects such as a new weapons system, needing to be broken down into numerous subsystems. The subsystems most likely will also need to be broken down and it continues until a measurable level of detail is reached. For example, last year ACC compared concept number F220001, the F-22 Raptor Air Superiority Fighter, an entire aircraft, to concept F220013, Unique Life Support Equipment for F-22 Operations (HQ ACC, Solutions, 1998: 8), which is one component of the aircraft. The lack of flexibility is related to the problem of sparse HOQs. How do the blanks spaces (relationships scoring no correlation) in the QFD matrix affect the results and what can be done to remedy this problem?

Solutions

Modifications to QFD might help combat the problems encountered. Potentially, there are both short term and long term modifications for QFD. It is important to ensure QFD is not used for purposes it is not intended. Looking into the similarities of QFD and MAVT should also offer insight into QFD. The changes may be necessary but not sufficient for solving some problems. For other situations, there may be no method of solving the problem while remaining within the general framework of QFD.

Scale

The first issue of concern is the scale of the numbers used in QFD. In the previous discussion of scales, it was assumed that the customer demand importance scores are on a ratio scale. The scale of the other numbers used in QFD must also be established. Below, the different scales and why or why not each scale applies to QFD are discussed. The issues of scale being questioned are:

- What is the scale of the rating system of QFD (the 9-3-1)?
- What is the scale of the QFD score (the "How Much" block in the HOQ)?

ABSOLUTE SCALE

The first scale tested for applicability was the absolute scale. The only admissible transformation to maintain an absolute scale is $\phi(x) = x$. In QFD, the only possible relationship scores are 9-3-1-0; there is no identity $\phi(x) = x$. For example, consider $f(a) \geq 10$. If f is an absolute scale (such as counting), every admissible transformation φ is feasible,

$$f(a) \geq 10 \Leftrightarrow (\varphi \circ f)(a) \geq 10,$$

for the only admissible transformation is the identity transformation. Note that $f(a)$ does not need to be greater than or equal to 10 for the statement $f(a) \geq 10$ to be meaningful (Roberts, 1979: 72). Meaningfulness is different from the truth in that the only concern is whether or not it makes sense to make the assertion (Roberts, 1979: 72). If the relationship scores (9-3-1-0) in QFD are assumed to be on an absolute scale, once a relationship is scored in the HOQ and the necessary operations are performed, those operations must comply with the required identity transformation for the final scores to be meaningful on an absolute scale. The table below (and throughout the chapter) is a truncated version of the case study presented by Bahill and Chapman in 1993 for a fictional toothpaste manufacturer, ToothBrite, Inc. (Bahill and Chapman, 1993: 27).

Table 4: Absolute Scale Test (a)

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (1to 10)	Pleasing Appearance	Cost to Produce
Hygienic	7		9
Reasonable Cost	9	1	3
Score		9	90

$m_{21}^{(1)}$

$\phi\left(m_{21}^{(1)}\right)$

As seen in the table above in QFD when $m_{21}^{(1)} = 1$, $\phi\left(m_{21}^{(1)}\right) = 9$ therefore $\phi\left(m_{21}^{(1)}\right) \neq m_{21}^{(1)}$ and there is no identity. QFD final scores for the matrix cannot be on an absolute scale even if the 9,3, and 1 are on an absolute scale. The exception to this, is when the

importance scores and relationship scores are all 1 as in Table 5 (Bahill and Chapman, 1993: 27).

Table 5: Absolute Scale Test (b)

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (1to 10)	Pleasing Appearance	Cost to Produce
Hygienic	1		1
Reasonable Cost	1	1	1
Score		1	2

$m_{21}^{(1)}$

$\phi\left(m_{21}^{(1)}\right)$

For the quality characteristic, *pleasing appearance*, $m_{21}^{(1)} = 1$, $\phi\left(m_{21}^{(1)}\right) = 1$ therefore $\phi\left(m_{21}^{(1)}\right) = m_{21}^{(1)}$. Unfortunately, not only is this highly unlikely, it also means that each quality characteristic can only be related weakly to one customer demand, otherwise the transformation would be violated as in the case of the second column, *cost to produce*. "Absence of symbols or presence of only weak symbols indicates either that a customer requirement [demand] has not been adequately addressed or that a technical requirement [quality characteristic] has no significant relationship to the customers' wants" (Day, 1993: 71-72).

Ratio Scale

The next strongest scale is the ratio scale where $\phi(x) = \alpha x$ are the only permissible transformations. The 9-3-1 scale in QFD could potentially be ratio *if* when the scoring takes place, the 9-3-1 is well defined where:

- 3 is three times more correlated than 1.
- 9 is three times more correlated than 3 and nine times more correlated than 1.
- Scoring a zero means there is no correlation.
- A score may be any real number from 0 to 9.

The last condition stated above means that QFD scores cannot be restricted to the discrete quantities of 9, 3, 1 or 0. This stipulation applies because the ratio scale is continuous and a relationship in the QFD matrix could conceivably score any value between 0 and 9. If the scores are restricted, bias is introduced because the discrete scores only allow for the categories of 9, 3, 1 or 0. A relationship may actually rate a 7 but with the original QFD scale, it will receive a 9 although it is less correlated than other relationships scoring 9s. The question remains, are the scores in the HOQ ratio or not?

Table 6: Ratio Scale

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (1to 10)	Pleasing Appearance	Cost to Produce
c_1 Hygienic	7		9
⋮ ⋮			
c_n Reasonable Cost	9	1	3
Score		9	90

$m_{ij}^{(1)}$

$\sum_{i=1}^{n} c_i m_{ij}^{(1)}$

(Bahill and Chapman, 1993: 27)

where

c_i = weight for customer demand i

$m_{ij}^{(p)}$ = matrix #p relationship value (9-3-1-0) for row i, column j

Based on the admissible transformation, $\phi(x) = \alpha x$, $\alpha > 0$, the importance score may be multiplied by any real number greater than zero and it will still be on a ratio scale. This means the scores can be normalized so all of the importance scores (which QFD uses as weights) sum to one.

$$c_{j_{(norm)}} = c_j * \left(\frac{1}{\sum_{i=1}^{n} c_i} \right)$$

If QFD scores, $m_{ij}^{(1)}$, are transformed inside the matrix using an allowable transformation for a ratio scale, the relationship score for each cell becomes $\alpha \cdot m_{ij}^{(1)}$, and the final score equation for column j changes to $\sum_{i=1}^{n} c_i \left(\alpha m_{ij}^{(1)}\right) = \alpha \sum_{i=1}^{n} c_i m_{ij}^{(1)}$. The final scores will only change by the scalar α; the ranking and the intervals between the scores will also change by α. Furthermore, given the statement:

$$m_{ab}^{(1)} + m_{cb}^{(1)} > m_{de}^{(1)},$$

assume the numerical assignment m is unique up to a similarity transformation then m is transformed to km and the new equation is:

$$km_{ab}^{(1)} + km_{cb}^{(1)} > km_{de}^{(1)}$$

This is obviously equivalent to $m_{ab}^{(1)} + m_{cb}^{(1)} > m_{de}^{(1)}$ thus, assuming m is on a ratio scale, $m_{ab}^{(1)} + m_{cb}^{(1)} > m_{de}^{(1)}$ is meaningful (Suppes and Zinnes, 1963: 67). This implies that if the scores are on a ratio scale, it is acceptable to multiply the scores by a constant and sum the scores in each column in a QFD matrix. A ratio scale applies to the QFD scores if it is assumed (1) an alternative that scores nine weak relationships is equivalent to an

alternative with one strong relationship, (2) scoring three weak relationships is equivalent to scoring one moderate relationship, (3) scoring three moderate relationships is equivalent to scoring one strong relationship. However, this only works if the scores are multiplied through by a single constant, that is, all of the customer demands must have the same importance weight. Given $m_{ab}^{(1)} + m_{cb}^{(1)} > m_{de}^{(1)}$, it was demonstrated above that the elements in a column may be summed, but in QFD, each element is multiplied by a potentially different customer importance score. This leads to trying to make a comparison of $k_1 m_{ab}^{(1)} + k_2 m_{cb}^{(1)} > k_3 m_{de}^{(1)}$. This is not equivalent to the original statement unless $k_1 = k_2 = k_3$. This is obviously not the typical case in general and is not the case for ACC, so the elements in a column cannot be summed and still maintain ratio scale status. This is supported by Roberts (73), consider the statement:

$$f(a) + f(b) = 20 \tag{1}$$

"Thus, (1) might be the statement that the sum of the weight of a and the weight of b is a constant, 20" (Roberts, 1979: 73). This is not meaningful if f is a ratio scale, because if $f(a) + f(b) = 20$, then $\alpha f(a) + \alpha f(b) = 20\alpha$ and $20\alpha \neq 20$ for $\alpha \neq 1$. However, saying $f(a) + f(b)$ is constant for all a, b is meaningful if f is a ratio scale.

Now, consider the statement:

$$f(a) + g(a) \text{ is constant} \tag{2}$$

"If f and g are both ratio scales, then to be meaningful, the truth or falsity of (2) should be unchanged under (possibly different) admissible transformations of each scale" (Roberts, 1979: 74). Assume $\varphi(x) = \alpha x$, $\alpha > 0$ and $\varphi'(x) = \beta x$, $\beta > 0$ then the statement (2) should hold if and only if

$$\alpha f(a) + \beta g(a) \text{ is constant} \tag{3}$$

But (3) might not be true even if (1) is. This is corroborated by assuming if $f(a) = -g(a)$ for all a, then $f(a) + g(a) = 0$, for all a; but if $\alpha \neq \beta$ and $f(a)$ is not constant, then $\alpha f(a) + \beta g(a) = (\alpha - \beta)f(a)$ is not constant and (2) is not meaningful if f and g are ratio scales (Roberts, 1979: 74). Hence, the elements in the columns of QFD cannot be summed after multiplying the relationship scores by customer demand scores and have the final score be meaningful on a ratio scale. A significant result of this is that since the final scores of one HOQ are not on a ratio scale, they cannot be carried over to the next HOQ and used as weights.

Further problems with using the ratio scale for QFD exist. The ratio scale has a natural zero that exists "when there is a satisfactory answer to the question: Is there a real meaning to having nothing or none of the quantity being measured" (Miller and Starr, 1967: 92). In QFD, the matrix is often over 50% uncorrelated. How is a column with mostly zeros comparable to one with few or none? A ratio of 3:0 is not possible. Day asserts that there should be no row or column with no relationship or only weak symbols (Day, 1993: 71). One course of action may be to delete the low or non-scoring columns (quality characteristics) making a note of why the column(s) were removed in the documentation of the QFD process.

INTERVAL SCALE

The allowable transformations for the interval scale are, $\phi(x) = \alpha x + \beta$, $\alpha > 0$, known as positive linear transformation (Roberts, 1979: 65). For this scale to apply a zero (an origin) must exist to anchor the scale in order to give the score meaning. Now assume the $m_{ij}^{(1)}$ are on an interval scale. This means the differences between scores may be

compared. For example measuring temperature (excluding the Kelvin scale which is ratio), it may be stated that the difference between today's and yesterday's maximum temperatures is -0.5°F, but it is meaningless to say the ratio of today's maximum temperature to yesterday's is 15°F/20°F = 0.75 (Suppes and Zinnes, 1963: 8-9). If an admissible transformation for an interval scale is performed on the QFD scores inside the matrix, the following holds:

$$\phi\left(m_{ij}^{(1)}\right)=\alpha \cdot m_{ij}^{(1)}+\beta$$

Substituting this transformation into the equation for the overall scores of the HOQ, $\left(\sum_{i=1}^{n} c_i m_{ij}^{(1)}\right)$, results in:

$$\begin{aligned}\sum_{i=1}^{n} c_i\left(\alpha \cdot m_{ij}^{(1)}+\beta\right) &= \sum_{i=1}^{n}\left(c_i \cdot \alpha \cdot m_{ij}^{(1)}+c_i \cdot \beta\right) \\ &= \alpha \sum_{i=1}^{n}\left(c_i \cdot m_{ij}^{(1)}\right)+\beta \sum_{i=1}^{n} c_i\end{aligned}$$

However, given $m_{ab}^{(1)}+m_{cb}^{(1)}>m_{db}^{(1)}$ assume the numerical assignment m is unique up to a linear transformation, then m is transformed to $km + l$. Resulting in:

$$\left(km_{ab}^{(1)}+l\right)+\left(km_{cb}^{(1)}+l\right)>\left(km_{db}^{(1)}+l\right)$$

which does not reduce to $m_{ab}^{(1)}+m_{cb}^{(1)}>m_{db}^{(1)}$. To prove addition is meaningless on an interval scale, a specific counterexample is shown. Let

$m_{ab}^{(1)}=1,\ m_{cb}^{(1)}=3,\ m_{db}^{(1)}=3,\ k=1,\ l=-1$. The equation $m_{ab}^{(1)}+m_{cb}^{(1)}>m_{db}^{(1)}$ then becomes

$$1+3>3.$$

But substituting the transformed values of $m_{ab}^{(1)}$ and $m_{cb}^{(1)}$ into the equation gives

$$(1*1 - 1)+(1*3 - 1)>(1*3-1)$$

or

$$0 + 2 > 2,$$

which does not have the same truth value as $1 + 3 > 3$ (Suppes and Zinnes, 1963: 67-68). Hence, within one HOQ it is not possible to maintain an interval scale throughout the QFD process because the scores in the columns are summed to obtain the final score.

COMBINING RATIO AND INTERVAL SCALES

The discussion above proves that the relationship scores inside the matrix cannot be interval. However, the scales for measurement may be combined. In the segment on ratio scales, it was shown that if strict rules are followed a ratio scale can be maintained inside the relationship portion of the HOQ. Recall, the 9-3-1 scale in QFD could potentially be ratio *if* when the scoring takes place, the 9-3-1 is well defined where:

- 3 is three times more correlated than 1.
- 9 is three times more correlated than 3 and nine times more correlated than 1.
- Scoring a zero means there is no correlation.
- A score may be any real number from 0 to 9.

From the discussion on ratio scales if the scores are on a ratio scale, it is not acceptable to multiply the scores by a constant and sum the scores in each column in a QFD matrix to maintain a ratio scale. However, the transformations on the relationship scores result in column scores that are meaningful on an interval scale.

Table 7: HOQ 1

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	IMPORTANCE	Quality Characteristic 1	Quality Characteristic 2
Customer Demand 1	c_1	$m_{11}^{(1)}$	$m_{12}^{(1)}$
Customer Demand 2	c_2	$m_{21}^{(1)}$	$m_{22}^{(1)}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$
Customer Demand n	c_n	$m_{n1}^{(1)}$	$m_{n2}^{(1)}$
Score		$\sum_{i=1}^{n} c_i m_{i1}^{(1)}$	$\sum_{i=1}^{n} c_i m_{i2}^{(1)}$

where, c_i = importance score for customer demand i

$m_{ij}^{(p)}$ = HOQ #p relationship value (9-3-1-0) for row i, column j

The admissible transformation for the interval scale is $\phi(x) = \alpha x + \beta$, $\alpha > 0$. Assume c_i and $m_{ij}^{(p)}$ are on a ratio scale. Using the first column of the matrix above the transformation, consider the statement

$$\sum_{i=1}^{n} c_i m_{i1}^{(1)} > \sum_{i=1}^{n} c_i m_{i2}^{(1)} \tag{4}$$

To show $m_{i1}^{(1)}$ is unique up to a linear transformation $\phi\left(m_{i1}^{(1)}\right)$ substitute $\phi\left(m_{i1}^{(1)}\right) = \alpha m_{i1}^{(1)} + \beta$ into equation 4, which gives

$$\sum_{i=1}^{n} c_i \left[\alpha m_{i1}^{(1)} + \beta\right] > \sum_{i=1}^{n} c_i \left[\alpha m_{i2}^{(1)} + \beta\right]$$

$$\alpha \sum_{i=1}^{n} c_i \left[m_{i1}^{(1)} + \beta\right] > \alpha \sum_{i=1}^{n} c_i \left[m_{i2}^{(1)} + \beta\right]$$

$$\sum_{i=1}^{n} c_i m_{i1}^{(1)} + \sum_{i=1}^{n} c_i \beta > \sum_{i=1}^{n} c_i m_{i2}^{(1)} + \sum_{i=1}^{n} c_i \beta \qquad (5)$$

and equation 5 can be reduced to equation 4. Hence, equation 4 is meaningful for an interval scale. Furthermore, it can be shown for any $m_{j1}^{(1)}$ that $\alpha = c_j$ and $\beta = \sum_{\substack{i=1 \\ i \neq j}}^{n} c_i m_{i1}^{(1)}$,

resulting in:
$$\phi\left(m_{j1}^{(1)}\right) = c_j \left(m_{j1}^{(1)}\right) + \left(\sum_{\substack{i=1 \\ i \neq j}}^{n} c_i m_{i1}^{(1)}\right)$$

This can be repeated for each column. Additionally, when linking houses, QFD transforms the final scores of one HOQ into weights and carries them over to the next HOQ. It has just been shown that the final column scores are on an interval scale. However, the scores need to be on a ratio scale to use them as weights. This is demonstrated in the following example.

Table 8: Customer Demands versus Quality Characteristics – Linking HOQs

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (1to 10)	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Tidy Tip	10		3	9		
Stays Put	4	3				
Hygienic	7			9		
Squeezable	4	3		1		
No Waste	6	1				
Reasonable Cost	9		1	3	9	
Attractive Container	8	3	9	1	9	
Time to Market	5		1	3	3	9
Return on Investment	9			3	9	3
Original Score		54	116	234	249	72
Original Rank		5	3	2	1	4
Relative Importance (score/sum of all scores)		0.07	0.16	0.32	0.34	0.10
Difference		0	62	180	195	18
INTERVAL Transformation $\alpha x + \beta, \alpha > 0$						
Transformed Score $\alpha = 0.25$ $\beta = 100$		113.5	129	158.5	162.25	118
Rank		5	3	2	1	4
Relative Importance (score/sum of all scores)		**0.17**	**0.19**	**0.23**	**0.24**	**0.17**
Difference		0.0	15.5	45.0	48.8	4.5
RATIO Transformation $\alpha x, \alpha > 0$						
Transformed Score $\alpha = 0.25$		13.5	29	58.5	62.25	18
Rank		5	3	2	1	4
Relative Importance (score/sum of all scores)		0.07	0.16	0.32	0.34	0.10
Difference		0.0	15.5	45.0	48.8	4.5

(Bahill and Chapman, 1993: 27)

Given the final scores from the HOQ in Table 8 with the column scores on an interval scale, the allowable transformations for the interval scale, $\phi(x) = \alpha x + \beta$, $\alpha > 0$, may be performed on the scores. If $\alpha = 0.25$ and $\beta = 100$, the transformed column scores 113.5, 129, 158.5, 162.25, and 118 are still meaningful on an interval scale. However, the relative importance of the quality characteristics in Table 8 are different for the

transformed scores on the interval scale. By transforming the scores, using a legal transformation for the interval scale, the meaning of the scores on an interval scale is maintained, but the weight for each quality characteristic is different (as shown by the relative importance). Thus, scores on an interval scale cannot be used as weights. In order to use the column scores as weights in the next HOQ, they must be on a ratio scale. Notice in Table 8 the relative importance remains the same after an allowable transformation on the ratio scale ($\phi(x) = \alpha x$, $\alpha > 0$) is performed.

Furthermore, the differences between scores can be compared and they will be the same relative distance from each other as the original scores. Since *amount of deformation* is the lowest scoring quality characteristic, it is subtracted from each of the quality characteristics for each set of scores. The ratios between the differences stay the same:

Table 9: Ratios of Differences

RATIO OF DIFFERENCE	Original		Interval		Ratio	
$\frac{\text{Amount of Deformation} - \text{Amount of Deformation}}{\text{Pleasing Appearance} - \text{Amount of Deformation}}$	$\frac{0}{62}$	0.0	$\frac{0.0}{15.5}$	0.0	$\frac{0.0}{15.5}$	0.0
$\frac{\text{Pleasing Appearance} - \text{Amount of Deformation}}{\text{Cost to Produce} - \text{Amount of Deformation}}$	$\frac{62}{180}$	0.34	$\frac{15.5}{45.5}$	0.34	$\frac{15.5}{45.5}$	0.34
$\frac{\text{Cost to Produce} - \text{Amount of Deformation}}{\text{Selling Price} - \text{Amount of Deformation}}$	$\frac{180}{195}$	0.92	$\frac{45.5}{48.8}$	0.92	$\frac{45.5}{48.8}$	0.92
$\frac{\text{Selling Price} - \text{Amount of Deformation}}{\text{Time to Develop} - \text{Amount of Deformation}}$	$\frac{195}{18}$	10.83	$\frac{48.8}{4.5}$	10.83	$\frac{48.8}{4.5}$	10.83

It is possible to transform scores from an interval scale to a ratio scale by comparing ratios of differences. Unfortunately, there is no anchor or set zero for the final QFD scores to use. One approach may be to simply subtract the lowest score from all scores as was done above. The problem with this approach is that for the lowest alternative,

amount of deformation, the difference is zero. If this value is to be used to help calculate a row weight, the presence of a zero creates major problems (Day, 1993: 102). It sets the lowest scoring alternative to zero, it will not be counted and cannot be carried over to the next table. An alternative cannot be thrown out merely because it scores the lowest. The alternative merits some consideration or it would not have been included in the first place.

ORDINAL SCALE

The permissible transformations for the ordinal scale are monotonic increasing transformations, $\phi \rightarrow f(\phi)$, where f is any strictly increasing real-valued function (Krantz, et al, 1971: 11). This could apply to the scores in QFD since 9 > 3 > 1. In QFD, a 9 is a strong correlation, a 3 is a moderate correlation and a 1 is a weak correlation. It allows the alternatives to be rank ordered. However, the only allowable transformation is, $x \geq y$ if and only if $\phi(x) \geq \phi(y)$, a (strictly) monotone increasing transformation. This does not allow QFD to weight and sum the scores and carry them into the next table.

According to the definition above, for the QFD scores to be ordinal, order must be preserved under any transformation. Regardless of what numbers are used to represent the strength of the correlation; the order of the scores should be the same. To check the validity of the numbers in QFD as an ordinal scale the final scores of one HOQ using three different ordinal scales, the original 9-3-1, 5-3-1, and 3-2-1 are compared (see Table 10). Since the ranks using different ordinal scales do not agree (i.e. order is not preserved), it cannot be said within one HOQ which quality characteristics are more strongly tied to the customer demands. Thus, by establishing that the scores are ordinal

and consistent throughout the HOQ does not guarantee the final results are also ordinal and consistent.

Table 10: Ordinal Test

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (1to 10)	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Tidy Tip	10		3	9		
Stays Put	4	3				
Hygienic	7			9		
Squeezable	4	3		1		
No Waste	6	1				
Reasonable Cost	9		1	3	9	
Attractive Container	8	3	9	1	9	
Time to Market	5		1	3	3	9
Return on Investment	9			3	9	3
Score (9-3-1)		54	116	234	249	72
Rank (9-3-1)		5	3	2	1	4
Difference (in score of *x* and the lowest)		0	62	180	195	18
Score (5-3-1)		54	84	166	145	52
Rank (5-3-1)		4	3	1	2	5
Difference (in score of *x* and the lowest)		2	32	114	93	0
Score (3-2-1)		38	58	109	88	33
Rank (3-2-1)		4	3	1	2	5
Difference (in score of *x* and the lowest)		5	25	76	55	0

(Bahill and Chapman, 1993: 27)

NOMINAL SCALE

According to Roberts, a nominal scale is one in which all one-to-one functions ϕ define admissible transformations. The nominal scale could not apply to QFD because it does not allow any mathematical transformations to be performed with the numbers because

the actual number has no significance. Therefore, it would not allow the scores to be transformed into weights and used in the next HOQ. An example of how this scale works is for numbers on uniforms. For example, in football, quarterbacks (10 - 20) often get low numbers and linebackers get numbers closer to 50. This does not mean that either player is more important or stronger. Within the HOQ, the 9s, 3s and 1s are comparable because categories (9 – strongly correlated, 3 – moderately correlated, 1 – weakly correlated) are assigned. However, once the relationship scores are multiplied by weights and summed in columns, the final scores are not nominal because the transformation performed on the scores is not one-to-one. In the table below (Bahill and Chapman,1993: 27), two different sets of weights and scores have the same results. Hence, QFD scores are not meaningful with a nominal scale.

Table 11: Nominal Test

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (1 to 10)	Pleasing Appearance	Cost to Produce
Hygienic	$2\frac{2}{3}$		9
Reasonable Cost	3	9	1
Score		27	27

FINDINGS

QFD needs rules to ensure the scale of the customer demands importance scores (c_i) and the relationship scores $\left(m_{ij}^{(p)}\right)$ inside the matrix are on ratio scales. If ratio scales can be

maintained for all c_i and $m_{ij}^{(p)}$ it has been proven that the column scores are on an interval scale. It is important to ensure the final scores are not misconstrued. Having the scores on an interval scale is beneficial because it potentially allows the scores to be used in mathematical programming however, it prohibits houses from being linked. Furthermore, "the column weights that are calculated during the development of the QFD matrix *should not* be used to determine priority items. They represent an artificial number and do not consider key issues" (Day, 1993: 106). Further research must be done on the customer demands such as "customer competitive evaluations, complaints, sales points or goals" (Day, 1993: 106). If the column weights support an engineering characteristic based on the relationships in the HOQ then it is an added bonus. However, a high scoring column may not have a significant impact on customer satisfaction. When used as originally intended, to identify the relationship of the "voice of the customer" to operational competencies, as long as scores in the first HOQ are not used as weights, QFD is fine. When ACC starts the use the scores in measurement capacities, depending upon how the scores are used, ACC risks obtaining results that could be misinterpreted or inconsistent.

Normalization

Normalization is explored to gain further insight into the scores in QFD The question here is what happens if the QFD matrix is normalized? Are the initial assumptions still valid? There are various ways to normalize numbers, and there are a few different sets of numbers in QFD that could be normalized. The first area is the customer demands. These have initial importance ratings that come from customers surveys, focus groups and research by the QFD users. If it is assumed that these are on a ratio scale with the

admissible transformation, $\phi(x) = \alpha x$, $\alpha > 0$, the importance score may be multiplied by any real number greater than zero and it will still be meaningful on a ratio scale. This means the importance scores may be normalized so they sum to one. By requiring the weights to sum to one, the result after multiplying the weights by the relationship scores also lies between zero and one (J. R. Miller, 1970: 42). Thus for a final column score in QFD, it is possible to score between 0 and 9. The column scores are between 0 and 9 because that is the range of possible relationship scores inside the HOQ; a relationship can score a 9, 3, 1, or 0. If a quality characteristic is strongly related to every customer demand and scores a 9 in every block of the column for that quality characteristic, the final score for the column will be 9.

$$c_{j(norm)} = c_j * \left(\frac{1}{\sum_{i=1}^{n} c_i} \right)$$

This is significant because QFD uses these scores as weights. Once the scores are normalized, it aids in comparing QFD to MAVT. Many QFD users convert importance absolute weights to percentages so the degree of importance of each customer demand sums to 100, however, the absolute weights are used in computations (Akao, 1990: 29, 40). Normalization is beneficial because the results now have more intuitive meaning than the original QFD scores in the 10,000s.

Table 12: Normalization

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (1to 10)	Normalized Importance (0 to 1)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Tidy Tip	10	0.130	9	3			1			5	9		
Retains Shape	4	0.052			1		1	3	9	1	1		
Stays Put	4	0.052						3	3				
Hygienic	7	0.091	1	9							9		
Squeezable	4	0.052			9		1		3		1		
Easy Open	6	0.078	1			9					3		
No Waste	6	0.078	3	1	3		9		1				
Small Footprint	5	0.065						9	1				
Reasonable Cost	9	0.117								1	3	9	
Attractive Container	8	0.104	3					1	3	9	1	9	
Time to Market	5	0.065								1	3	3	9
Return on Investment	9	0.117									3	9	3
Original QFD Score			145	99	58	54	72	77	95	140	256	249	72
Original Rank			3	5	10	11	8	7	6	4	1	2	8
Score (normalized)			1.88	1.28	0.75	0.70	0.93	1	1.23	1.81	3.32	3.23	0.93
Rank (normalized)			3	5	10	11	8	7	6	4	1	2	8

(Bahill and Chapman, 1993: 28)

The matrix in Table 12 shows the scores in the bottom of the HOQ for the original QFD and the normalized version. The main difference is that the scores using the normalized customer attributes are between 0 and 9. The column scores for the normalized version give the user a better indication of the relative differences between the scores. It becomes more apparent that the top two quality characteristics, *cost to produce* and *selling price* are significantly better than the next highest characteristics, *amount of mess* and *pleasing appearance.* Furthermore, the normalized scores also show that the bottom six

characteristics are fairly close in score and decisions about these characteristics should not be made based on the scores of this table alone.

If desired, the numbers inside the table may be normalized and maintain the ratio scale because the numbers are merely multiplied by a constant. There are many ways to normalize numbers; however to maintain the meaningfulness of the numbers in the matrix, the constant used is the inverse of the sum of the scores inside the matrix.

$$m_{ij(norm)}^{(1)} = \alpha \cdot m_{ij}^{(1)}$$

$$\text{where, } \alpha = \frac{1}{\sum_j \sum_i m_{ij}^{(1)}}$$

Performing this transformation on the relationship scores means the final scores now lie between zero and one. However, when the QFD team assigns the relationship scores, it is best to use numbers the user feels most comfortable with and the 0-9 scale may offer the most accurate results. The scoring system can always be rescaled after it is evaluated so the strongest relationship scores a 1 and no relationship receives a 0. This would be also be beneficial in a comparison of QFD to MAVT.

The Structure of QFD

How do the blanks in the QFD matrix affect the results and what can be done to remedy this problem? The sparsity of the matrices is a significant problem for QFD when used as a planning tool. Some actions are simple needing only one or two levels of detail, whereas other actions may be complicated long-term projects such as a new weapons system, needing to be broken down into numerous subsystems. The subsystems most likely will also need to be broken down and it continues until a measurable level of detail is reached. QFD matrices are not flexible enough to deal with this. This inflexibility is

attributed to the fact that when using QFD for planning, *all* items are transferred to the next level, not just the high priority items (Day, 1993: 202). A hierarchy, like those used for structuring decisions in MAVT, would be a better format for such large complicated plans. Proper structuring of objectives in a hierarchy results in a deeper/more accurate understanding of what one should care about in the decision context. Problem structuring helps clarify the decision context, define fundamental objectives and provide the basis for the use of quantitative modeling (Keeney, 1992: 69). By structuring problems using hierarchies, MAVT avoids the issue of the blanks (scores of "no relationship") in the QFD matrix altogether. A hierarchy is an excellent way to structure fundamental objectives so as to help simplify a complex decision situation. "A good objectives hierarchy helps to remove inappropriately narrow anchors for creating alternatives" (Keeney, 1992: 202). With a hierarchy, the required level of specificity for each objective is chosen on an individual basis.

Comparing QFD to MAVT

MAVT is an excellent way to evaluate alternatives because it applies mathematical theory to complex, sometimes ambiguous decision situations. The objectives of the decision situation can be structured in meaningful way by using a hierarchy (Keeney and Raiffa, 1993: 41). Objectives are divided into lower-level objectives of more detail to clarify the problem. Scoring functions are established at the lowest level. "A scoring function is a unique rule that assigns a unique worth [value] score in points to every possible value of some physical performance measure" (J. R. Miller, 1970: 38). The scoring functions in MAVT correspond to the 9-3-1 scoring system in QFD; however, QFD evaluates the alternatives in a more subjective way. Moreover, the scale used in

MAVT to measure value is continuous and the original 9-3-1 QFD scale is not. The hierarchical structure of MAVT also allows for more specification. It is flexible with regard to levels as opposed to QFD where the user is restricted to the levels of the matrices and cannot delve further into a customer attribute or engineering characteristic than the lowest HOQ.

The matrix form of QFD with the linked HOQs provides an easy transition to the hierarchical form of MAVT. However, the results are the same regardless of the format. It is the initial assumptions that need to be reformulated to give QFD mathematically sound results. If QFD were converted to MAVT, value functions for the horizontal elements across the top of the HOQ would be required. In the case of linked houses, value functions would only be necessary in the last house.

MAUT and QFD are both useful processes that can complement each other when used together, ideally resulting in better decisions or at least in better analysis to base decisions upon. QFD is sufficient if the only results desired are a relative ranking of the alternatives on the lowest level of the process. However, if there is any desire for sensitivity analysis or further analysis using the results of QFD, unless exquisite care is taken in the scoring and documentation throughout the entire procedure, the numbers do not have any meaning beyond a relative rank and should not be used for calculations.

MAVT has foundations in mathematics, which allows sensitivity analysis. Unfortunately, it is time consuming and takes experience and practice to correctly model the decision situation to adequately embrace the decision maker's values.

Rather than waste the time and effort that organizations have already put into QFD processes, implementing a few simple rules may help immeasurably.

Rules for QFD

1. Assume the importance scores for the customer demands are on a ratio scale.
2. Normalize the importance scores so they sum to one and can be used as weights.
3. Ensure the relationship scoring system is on a ratio scale.
    a. 3 is three times more correlated than 1
    b. 9 is three times more correlated than 3 and nine times more correlated than 1
    c. Scoring a zero means there is no correlation.
    d. A score may be any real number from 0 to 9.
    e. Scoring nine weak (1) relationships is equivalent to an alternative with one strong (9) relationship,
    f. Scoring three weak (1) relationships is equivalent to scoring one moderate (3) relationship
    g. Scoring three moderate (3) relationships is equivalent to scoring one strong (9) relationship.
4. The final scores from one HOQ are ratio *if* the customer demands are all equally important (i.e. the customer demands all score the same importance weight) *and* all of the rules above have been strictly adhered to.
5. Transform the scores from one HOQ into weights for another providing they are on a ratio scale.
6. Remember that the final scores are only a *recommendation*. "The column weights that are calculated during the development of the QFD matrix *should not* be used to

determine priority items. They represent an artificial number and do not consider key issues" (Day, 1993: 106).

Revamping ACC's Process

ACC's problem with inconsistent use of QFD is that as the MPP moves through the QFD process from house to house, it changes from correlations to performance and back to correlations. Day suggests using what he calls a research and development QFD matrix. This is separate from the linked houses used to evaluate the process, to represent "how to do" a customer demand or in ACC's case a task, as opposed to "how to measure it." A research and development matrix can capture new alternatives that may be suggested as result of team discussions.

EXAMPLE

The purpose of this chapter is to demonstrate the modifications suggested in chapter three. Two examples of QFD in use are shown. The first example is a heuristic case study presented by Bahill and Chapman in 1993 for a fictional toothpaste manufacturer, ToothBrite, Inc. The objective is to redesign the product to regain ToothBrite's market share which was lost when Crest® came out with a new container called the Neat Squeeze dispenser (Bahill and Chapman, 1993: 25). This is a simple example that uses QFD to plan a new product (a toothpaste dispenser). It was selected because it uses QFD as was originally intended, for a manufacturing process, and the example demonstrates how HOQs may be linked.

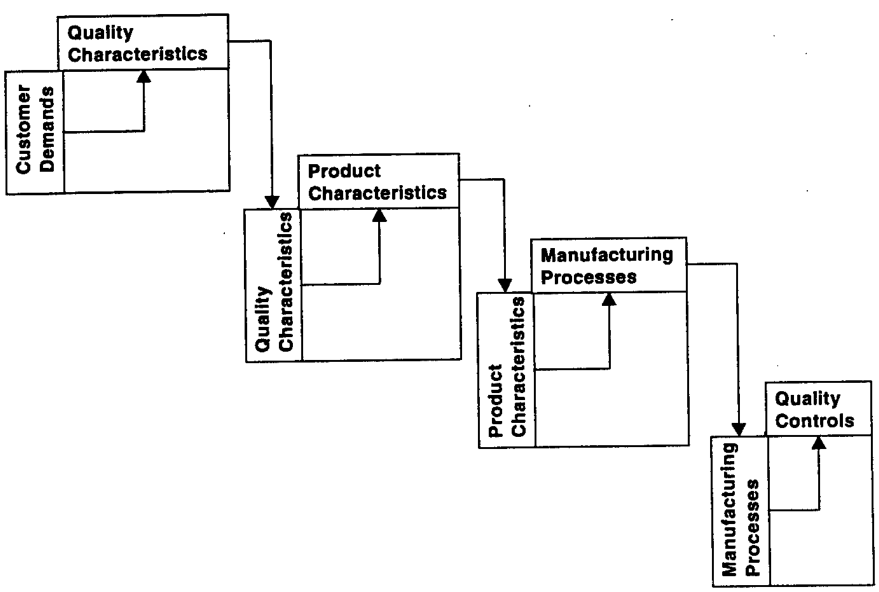


Figure 7: The QFD waterfall chart for ToothBrite (Bahill and Chapman, 1993: 25)

The second example is ACC's version of the Air Force Modernization Planning Process. The goal is to choose the modernization initiatives (concepts) that will offer the most combat capability to the Air Force force structure. Ultimately, the results of the MPP provide input and guidance to the ACC budget. ACC's version of QFD also links numerous houses.

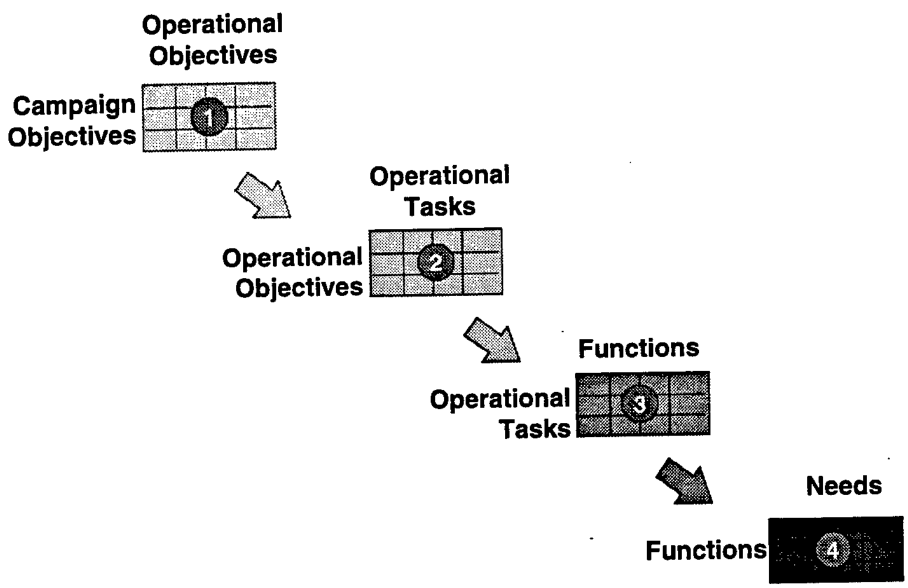


Figure 8: Combat Capability Scoring Flow (HQ ACC MPP overview, 1998: 21)

For each example the original QFD process is shown first. Subsequently, the recommended solutions to the problems explained and demonstrated in chapter three are illustrated along with the effects of the solutions.

QFD Example from Bahill and Chapman - No Modifications

This example shows how QFD can be used to help design a product or process. QFD can also be used to help select the best alternative concept" (Bahill and Chapman, 1993: 29). This particular example was chosen because it runs through the entire QFD process as

originally intended. It starts with customer demands and flows through four houses of quality until it reaches the bottom level of quality controls.

The first HOQ relates the customer demands to quality characteristics. The customer does not refer merely to the person choosing the toothpaste off the shelf in a store but "includes all people who should provide input for the system design: buyers, store managers, mothers, stockholders, employees, company management, and the company's Manufacturing and Marketing departments" (Bahill and Chapman, 1993: 25). The objective of this matrix is to relate the customer demands to measurable quality characteristics that the engineering department can understand and use to satisfy the customers. The relationship strength is scored using the system: 9 (◎) for a strong correlation, 3 (O) for a moderate correlation, 1 (Δ) for a weak correlation, and 0 (blank) for no correlation. "The attention to the customer is the main purpose of the QFD chart. The chart and its results are not as important as concentrating on the 'voice of the customer' rather than the 'voice of the manufacturer'" (Bahill and Chapman, 1993: 26). In the first QFD chart, *cost to produce* and *selling price* are the most important quality characteristics because of their strong correlation to customer demands.

Table 13: The first QFD chart – Customer Demands versus Quality Characteristics

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (1 to 10)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	10	9	3			1			5	9		
Retains Shape	4			1		1	3	9	1	1		
Stays Put	4						3	3				
Hygienic	7	1	9							9		
Squeezable	4			9		1		3		1		
Easy Open	6	1			9					3		
No Waste	6	3	1	3		9		1				
Small Footprint	5						9	1				
Reasonable Cost	9								1	3	9	
Attractive Container	8	3					1	3	9	1	9	
Company												
Time to Market	5								1	3	3	9
Return on Investment	9									3	9	3
Score		145	99	58	54	72	77	95	140	256	249	72
Rank		3	5	10	11	8	7	6	4	1	2	8

(Bahill and Chapman, 1993: 27)

The second HOQ for the ToothBrite case study relates the quality characteristics from the first house to product characteristics. The scores in the bottom of the house become the weights for the next house. Comparing quality characteristics and product characteristics in the second HOQ helps investigate the components of the design and is useful for looking at alternative designs. However, to keep the size of the chart from becoming unwieldy with too many characteristics, it may help to create a second QFD chart for each alternative design. "The questions become, 'This is What I am going to measure, now How will I build the product to make it optimum?'" (Bahill and Chapman, 1993: 31).

Table 14: The second QFD chart – Quality Characteristics versus Product Characteristics

QUALITY CHARACTERISTICS V. PRODUCT CHARACTERISTICS	Weights	Double Lead Thread	Size of Hole in Tip	Material Thickness	Material Type	Size of Dashpot	Viscosity of Dashpot	Weight of Container	Size of Container	Printing on Label	Shape of Container
Amount of Mess	145		1	1	3	3	3				
Amount of Pull-back	99		3	3	9	3	9				
Amount of Pressure	58		3	3	9		9				
Amount of Effort	54	9	1		1						
Amount of Waste	72		3	1	3		1		3		1
Counter space	77							3	9	1	9
Amount of Deformation	95		1	1	9				1		1
Pleasing Appearance	140				1				3	9	3
Cost to Produce	256			1	9	1	3	1	3	3	9
Selling Price	249			1	3	1	1		1	3	3
Time to Develop	72				3	1	3			1	3
Score		486	981	1288	6380	1309	3153	487	2441	2924	4547
Rank		10	8	7	1	6	3	9	5	4	2

(Bahill and Chapman, 1993: 30)

In the second HOQ, *material type* and *shape of container* are the highest scoring product characteristics. Notice they are both strongly correlated to the quality characteristic, *cost to produce*, which has the highest weight. The scores from the second HOQ tell the manager where he/she should allocate talent and money for tradeoff studies (Bahill and Chapman, 1993: 33). Once this chart is complete, the product characteristics must be translated into manufacturing processes. The third HOQ for ToothBrite shows the transition from product characteristics to manufacturing processes. The processes are listed in the approximate order in which they are accomplished.

Table 15: The third QFD chart – Product Characteristics versus Manufacturing Processes

PRODUCT CHARACTERISTICS v. MANUFACTURING PROCESSES	Weights	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label
Double Lead Thread	486		9	9	3		1	1		
Size of Hole in Tip	981		9	9	3		9			
Material Thickness	1288			9					3	
Material Type	6380		1	9	1	3		1	9	3
Size of Dashpot	1309		3			1			3	
Viscosity of Dashpot	3153		9	9	3				3	
Weight of Container	487		3			1				
Size of Container	2441		9			1	3		1	3
Printing on Label	2924									9
Shape of Container	4547		9	9	3	3			3	9
Score			116240	151515	33881	37018	16638	6866	90752	93702
Rank			2	1	6	5	7	8	4	3

(Bahill and Chapman, 1993: 31)

For third HOQ, the first two molding processes, *create mold* and *blow material* have the highest scores. This is not surprising since they are strongly correlated to six and five product characteristics respectively. The next highest ranked manufacturing process, *pasting or printing label*, is only strongly correlated to two product characteristics. "The manufacturing manager now knows which processes to develop and spend capital on" (Bahill and Chapman, 1993: 33). Once the strength of relationships for the manufacturing processes have been developed, the processes need to be mapped to the company's quality control capabilities. This is done by tying the manufacturing processes to the quality controls in the fourth HOQ. The fourth QFD chart looks for relationships between the manufacturing processes and quality control. The quality controls are the aspects of

the process that should be monitored and controlled during manufacturing (Bahill and Chapman, 1993: 32).

Table 16: The fourth QFD chart - Manufacturing Processes versus Quality Controls

MANUFACTURING PROCESSES V. QUALITY CONTROLS	Weights	Mold Dimensions	Material Controls	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flow rate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygiene Controls
Molding Process (Cap, Body, Bottom)															
Create Mold	116240	9													1
Blow Material	151515			9	3	3									
Remove Container	33881	3													1
Insert and Bond Liner	37018	1					9				1		1		
Inserting Toothpaste	16638							9							9
Screwing on Top	6866	1							9						3
Ultrasonic Weld Bottom	90752										3	3	9		1
Pasting or Printing Label	93702													9	1
Score		1191687		1363635	454545	454545	333162	149742	61794		309274	272256	853786	843318	504915
Rank		2		1	6	6	8	11	12		9	10	3	4	5

(Bahill and Chapman, 1993: 32)

The four houses have taken the customer's demands, related them to quality characteristics, which are then linked to product characteristics. These product characteristics are then related to ToothBrite's manufacturing processes and finally to their quality controls. From this analysis, the highest impact on satisfying customer demands is gained by attention to the *temperature controls*, followed by attention to the quality control of *mold dimensions*. The final HOQ shows which quality controls are critical and "deserve special experimentation and investment to ensure a quality product"

(Bahill and Chapman, 1993: 33). However, it is difficult to ascribe a meaning to the raw scores. Other than providing a general idea of their rank, the final scores after linking one or more HOQs are meaningless. Recall the permissible transformations for the ordinal scale are monotonic increasing transformations, $\phi \rightarrow f(\phi)$, where f is any strictly increasing real-valued function (Krantz, et al, 1971: 11). For the QFD scores to be ordinal, order must be preserved by a monotonic transformation function. Regardless of what numbers are used to represent the strength of the correlation, the rank of the scores should be the same. In chapter three when the numbers in QFD were assumed to be on an ordinal scale and were compared, the final ranks of the scores in one HOQ using three different ordinal scales (see Table 10) did not agree (i.e. order was not preserved). Thus, it cannot be said within any HOQ beyond the first one (quality characteristics versus customer demands) which *Hows* are more strongly tied to the *Whats* because there is no guarantee the final results are ordinal and consistent regardless of what scale the scores were established to be at the onset. Furthermore, since the only allowable transformation to maintain an ordinal scale is a (strictly) monotone increasing transformation, when QFD weights and sums the scores and carries them into the next table, the meaning of the scores is even further convoluted. Various fixes will be presented in an attempt to resolve the issues encountered with QFD. To reiterate, other than a mechanism for ranking, the QFD scores are meaningless. Further, unless the scales are consistent, even the rankings are suspect, as demonstrated in Table 10. While classic QFD provides a framework to identify relations between the voice of the customer and the organization's capabilities, great care should be taken in imparting any meaning to the final scores particularly in multiple house situations.

ToothBrite Fix 1: Normalization

The first recommended fix is normalization. This can be applied to any existing QFD matrix. To be able to normalize the scores for the customer demands it must be assumed the importance scores are on a ratio scale with the admissible transformation, $\phi(x) = \alpha x$, $\alpha > 0$. The attached importance score may be multiplied by any real number greater than zero and it will still be meaningful on a ratio scale. This implies the importance scores may be normalized by multiplying them by the reciprocal of the sum of the scores. By requiring the weights to sum to one, the result also lies between zero and one (J. R. Miller, 1970: 42). In this case, the weights are normalized to sum to one within each HOQ. The normalization is only applied to the weights because when scoring, it is best to use numbers the user feels most comfortable with so the 0-9 scale may offer more accurate results. One of the problems with QFD is that it can result in large scores at the end of the process that have no intuitive meaning. For example, in the fourth HOQ above (Table 16), it is difficult to tell the relative difference between a score of 1,363,635 and 272,256. Normalization provides output that is more meaningful because the normalized scores remain between 0 and 9, the original scale whereas the original QFD scores repeatedly weighted and summed, end up in the 100,000s. The column scores are between 0 and 9 because that is the range of possible relationship scores inside the HOQ; a relationship can score a 9, 3, 1, or 0. If a quality characteristic is strongly related to every customer demand and scores a 9 in every block of the column for that quality characteristic, the final score for the column will be 9. Normalization is also beneficial in comparing QFD to MAVT because the final scores now lie between zero and nine. The scores could be re-scaled to lie between zero and one. Using additive value functions

where the weights sum to one is what is most commonly used in practice in MAVT (Kirkwood 1997: 230). The full HOQs for each fix can be found in Appendix A.

Table 17: Fix 1 Normalization - Customer Demands v. Quality Characteristics

Original

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (1 to 10)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	10	9	3			1			5	9		
Retains Shape	4			1		1	3	9	1	1		
Stays Put	4						3	3				
Hygienic	7	1	9							9		
Squeezable	4			9		1		3		1		
Easy Open	6	1			9					3		
No Waste	6	3	1	3		9		1				
Small Footprint	5						9	1				
Reasonable Cost	9								1	3	9	
Attractive Container	8	3					1	3	9	1	9	
Company												
Time to Market	5								1	3	3	9
Return on Investment	9									3	9	3
Score		145	99	58	54	72	77	95	140	256	249	72
Rank		3	5	10	11	8	7	6	4	1	2	8

Fix 1

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (0 to 1)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	0.130	9	3			1			5	9		
Retains Shape	0.052			1		1	3	9	1	1		
Stays Put	0.052						3	3				
Hygienic	0.091	1	9							9		
Squeezable	0.052			9		1		3		1		
Easy Open	0.078	1			9					3		
No Waste	0.078	3	1	3		9		1				
Small Footprint	0.065						9	1				
Reasonable Cost	0.117								1	3	9	
Attractive Container	0.104	3					1	3	9	1	9	
Company												
Time to Market	0.065								1	3	3	9
Return on Investment	0.117									3	9	3
Score		1.883	1.286	0.753	0.701	0.935	1.000	1.234	1.818	3.325	3.234	0.935
Rank		3	5	10	11	8	7	6	4	1	2	8

Quality Characteristic	Original		Normalized	
	Score	Rank	Score	Rank
Amount of Mess	145	3	1.883	3
Amount of Pull-back	99	5	1.286	5
Amount of Pressure	58	10	0.753	10
Amount of Effort	54	11	0.701	11
Amount of Waste	72	8	0.935	8
Counter space	77	7	1.000	7
Amount of Deformation	95	6	1.234	6
Pleasing Appearance	140	4	1.818	4
Cost to Produce	256	1	3.325	1
Selling Price	249	2	3.234	2
Time to Develop	72	8	0.935	8

Comparing the scores for the original QFD example for ToothBrite to the normalized scores shows the ranks stay the same. However, comparing the relative differences between the normalized scores is more straightforward. The range of the scores could be from 0 to 9 but the highest scoring quality characteristic is *cost to produce* with a score of 3.325. It can now be seen that the nine lowest scoring quality characteristics are all close in importance.

Table 18: Fix 1 Normalization – Quality Characteristics v. Product Characteristics

Product Characteristic	Original		Normalized	
	Score	Rank	Score	Rank
Double Lead Thread	486	10	0.369	10
Size of Hole in Tip	981	8	0.745	8
Material Thickness	1288	7	0.978	7
Material Type	6380	1	4.844	1
Size of Dashpot	1309	6	0.994	6
Viscosity of Dashpot	3153	3	2.394	3
Weight of Container	487	9	0.370	9
Size of Container	2441	5	1.853	5
Printing on Label	2924	4	2.220	4
Shape of Container	4547	2	3.453	2

The comparison of the scores from the second HOQ also shows the top two product characteristics to be significantly better than the other eight. Normalizing the scores helps point out the differences between the product characteristic scores. Normalization is an important modification to the scores because the breakout of the scores is more apparent to the QFD user because the range of possible scores is known to be 0 to 9. This is more meaningful to the user because it is the same range as the relationships scores inside the HOQ. Comparing the scores of the final two HOQs from the ToothBrite example in Tables 19 and 20 allows similar conclusions about the scores to be made.

Table 19: Fix 1 Normalization – Product Characteristics v. Manufacturing Processes

Manufacturing Processes	Original		Normalized	
	Score	Rank	Score	Rank
Molding Process (Cap, Body, Bottom)				
Create Mold	116240	2	4.844	2
Blow Material	151515	1	6.314	1
Remove Container	33881	6	1.412	6
Insert and Bond Liner	37018	5	1.543	5
Inserting Toothpaste	16638	7	0.693	7
Screwing on Top	6866	8	0.286	8
Ultrasonic Weld Bottom	90752	4	3.782	4
Pasting or Printing Label	93702	3	3.905	3

Table 20: Fix 1 Normalization – Manufacturing Processes v. Quality Controls

Quality Controls	Original		Normalized	
	Score	Rank	Score	Rank
Mold Dimensions	1191687	2	2.180	2
Material Controls				
Temperature	1363635	1	2.495	1
Pressure	454545	6	0.832	6
Time	454545	6	0.832	6
Liner Attachment Inspection	333162	8	0.610	8
Toothpaste Flow rate	149742	11	0.274	11
Cap Attachment Torque	61794	12	0.113	12
Welding Controls				
Intensity	309274	9	0.566	9
Duration	272256	10	0.498	10
Pressure	853786	3	1.562	3
Labeling Pressure	843318	4	1.543	4
Cleanliness and Hygiene Controls	504915	5	0.924	5

ToothBrite Fix 2: Adjust the Scale to be Continuous

To accurately capture the effects of adjusting the scale to be continuous, the scoring team would have to reconvene and run through the entire QFD process again allowing relationships to be scored as any real number between 0 and 9. Additionally, the rules for ensuring the scale is ratio (see p. 44) would have to be adhered to. In lieu of demonstrating this modification, the actions required to ensure the scores are on a ratio scale are listed below.

Steps for Applying Rules for QFD to Adjust the Scale

1. Evaluate the importance scores for the customer demands ensuring they are on a ratio scale. This means if customer demand X scores a four and another customer demand, Y, receives a two, then X is twice as important to the customer as Y. Having the importance scores on a ratio scale can be accomplished by asking questions about the customer demands as they are scored. For example, if the range of scores is 0 to 10

the endpoints should be defined; scoring a 10 means that if this demand is not satisfied the customer will not buy the product and any demand scoring a 0 should be omitted because it is obviously not important to the customer. If a demand scores a 5 that implies it is half (5/10) as important as any demand scoring a 10, if a demand scores a 4 that implies it is 2/5 as important as any demand scoring a 10 and 4/5 as important as a demand scoring a 5. These comparisons should be made for all of the demands

2. Normalize the importance scores so they sum to one and can be used as weights.
3. Ensure the relationship scoring system is on a continuous ratio scale. The scoring team must agree upon what scoring a 9 actually means. This will be different for each HOQ because it depends on the relationship being scored. Once one level is defined, it will provide a baseline for the other scores.
    a. A score may be any real number from 0 to 9. For this step, use the scale the QFD scoring team is most comfortable with; some users prefer a 0 to 5 scale while others may prefer a 0 to 10 scale.
    b. 3 is three times more correlated than 1
    c. 9 is three times more correlated than 3 and nine times more correlated than 1
    d. Scoring a zero means there is no correlation.
    e. Scoring nine weak (1) relationships is equivalent to scoring three moderate (3) relationships and one strong (9) relationship.
    f. Scoring three weak (1) relationships is equivalent to scoring one moderate (3) relationship.

4. The final scores from one HOQ are ratio *if* the customer demands are all equally important (i.e. the customer demands all score the same importance weight) *and* all of the rules above have been strictly adhered. The final scores are interval if the importance scores and relationship scores are ratio.
5. Do not transform the scores from one HOQ into weights for another unless they are on a ratio scale. Note that if these weights are transformed, unless they are all equal (which is highly unlikely), the column scores of the new HOQ will be meaningless.
6. Remember that the final scores are only a *recommendation*. "The column weights that are calculated during the development of the QFD matrix *should not* be used to determine priority items. They represent an artificial number and do not consider key issues" (Day, 1993: 106).

APPLYING RULE 3 TO TOOTHBRITE

Of the rules listed above, one and three are probably the most important one because they ensure the importance scores and the relationship scores are on ratio scales. Having ratio scales implies the column scores are on an interval scale allowing the numbers to be used in some types of mathematical programs. In the first HOQ for the ToothBrite example, the relationship being scored is customer demands versus quality characteristics. Now that the scale is a continuous ratio scale, care must be taken to ensure the scores are well defined and the scoring team agrees upon the definition. In scoring relationships, first the team must assess if the customer demand can be measured by the quality characteristic. Next the team must decide how strong the relationship between the customer demand and the quality characteristic is. Suppose the team agrees that a 9 means the quality characteristic will have a strong direct impact on satisfying the customer demand. This

implies that scoring a 4.5 means that if the quality characteristic is controlled, it will have half as much impact on satisfying the customer demand. For example, the first quality characteristic is *amount of mess*, after the team decides that it is related to the customer demand *tidy tip*, the strength of that relationship must be decided. *Amount of mess* scores a 9 meaning it has a strong impact on satisfying the customer demand *tidy tip*; whereas it only scores a 3 against the customer demand *no waste*. This means *amount of mess* has three times the impact on satisfying *tidy tip* as it does in satisfying *no waste*. This train of thought for scoring must be applied to each HOQ in the QFD process.

For the second HOQ in the ToothBrite example, the quality characteristics are compared to product characteristics. Suppose the team agrees that a 9 means the product characteristic will have a strong direct impact on satisfying the quality characteristic. This implies that scoring a 4.5 means that if the product characteristic is accounted for it will have half as much impact on satisfying the quality characteristic. It is important to document what the scores mean to provide continuity not only for the QFD process, but also for the organization as a whole.

ACC Example – No Modifications

This example is included to demonstrate the modifications for QFD to a real world example currently used by ACC for their planning process. ACC's QFD scoring methodology uses the STT hierarchy to obtain a combat capability score for each concept. There are three distinct scoring phases broken down into particular activities. The purpose is to identify the input, output, controls, and core participants in each MPP phase. "ACC uses QFD as a systematic way of ensuring that the demands of the mission

drive modernization planning" (HQ ACC, MIP Handbook, 1998: 3). ACC interprets QFD as a decision analysis tool to model STT and develop relative combat capability weights for the various modernization initiatives under consideration (HQ ACC, MIP Handbook, 1998: 3). ACC employs a five-step process at each level of the STT hierarchy.

1. Identify the *Whats*
2. Prioritize the *Whats*
3. Identify the *Hows*
4. Relate *Hows* to *Whats*
5. Evaluate *Hows*

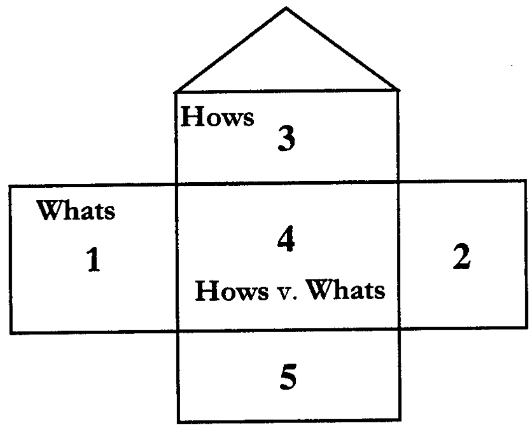


Figure 9: HOQ for ACC's Five Step Scoring Process (HQ ACC, MIP Handbook, 1998: A-4)

This process is restarted each time ACC links another house, transferring the *Hows* and their scores in block 5 to block 1 in the next HOQ. The three scoring phases in ACC's STT framework are the MAA, MNA and MSA. This example only deals with the QFD process as it is implemented in the first phase. In phase one, the MAA, the operational tasks the CINCs may ask warfighters to execute are identified. The inputs for this phase include DPG, AFDD 1, Air Force Executive Guidance, theater command input, regional Operations Orders, and Operational Plans. For the first HOQ in the ACC process, the relationship being scored in step 4 is campaign objectives (*Whats*) to operational objectives (*Hows*). "The analytical team starts at the top of a column and continues down to the bottom. When scoring each cell in a column each team member asks, "*What is the contribution of this operational objective, the 'How', to the accomplishment of this*

campaign objective, the 'What'" (HQ ACC, MIP Handbook, 1998: A-6). ACC uses the 9-3-1-0 scoring system for the relationships. ACC partitions the highest level objectives into two areas, for a Major Theater of War (MTW) there are five campaign objectives and for Small Scale Conflicts (SSC), there are three regional objectives. These are assigned weights according to the table below. The QFD tables for SSC (Appendix A) remain separate until the last HOQ for the MAA when they are recombined.

Table 21: Objective Weights

CAMPAIGN or REGIONAL OBJECTIVE	WEIGHT
Major Theater of War (MTW)	2
Small Scale Conflict (SSC)	1

Table 22: Campaign Objectives v. Operational Objectives

MTW CAMPAIGN OBJECTIVES V. OPERATIONAL OBJECTIVES	Rank	Initial Weight	Operational Objectives	Defeat air/space forces	Defeat air defense forces	Prevent sortie generation	Defeat ground forces	Defeat naval forces	Disrupt military support basis	Disrupt economic support basis	Disrupt political base	Disrupt C4I
Campaign Objectives				1	2	3	4	5	6	7	8	9
Establish aerospace supremacy	5	0.667	1	9	9	9						3
Establish maritime supremacy	1	0.133	2					9				3
Establish ground supremacy	4	0.533	3				9					3
Counter weapons of mass destruction	4	0.533	4	3		3	1	1	1		3	1
Eliminate war making will/ability	1	0.133	5						9	3	9	
				1	2	3	4	5	6	7	8	9
OO QFD Total				7.600	6.000	7.600	5.333	1.733	1.733	0.400	2.800	4.533
OO Rank				1	3	1	4	7	7	9	6	5

After the five steps are completed for first HOQ, the operational objectives (the *Hows*) and their associated scores are transposed to become the *Whats* in the next HOQ. The operational objectives are compared to operational tasks asking "*What is the contribution of this operational task, the How, to the accomplishment of this operational objective, the What?*"

Table 23: Operational Objectives v. Operational Tasks

MTW OPERATIONAL OBJECTIVES V. OPERATIONAL TASKS	Rank	Operational Tasks	Neutralize aircraft in-flight	Neutralize cruise missiles & UAVs in-flight	Neutralize ballistic missiles in-flight	Neutralize vehicles in space	Neutralize aircraft, cruise missiles and UAVs on the ground	Neutralize ballistic missiles & support on the ground	Neutralize airfield operating surfaces	Neutralize military support facilities	Neutralize naval vessels	Neutralize industrial production	Neutralize power production	Neutralize WMD production & storage	Neutralize weapons factories & storage sites	Neutralize lines of communication (LOCs)	Neutralize fixed forces	Neutralize advancing combat forces	Neutralize engaged ground forces	Neutralize fixed surface to air threats	Neutralize mobile surface to air threats	Neutralize air defense information collection/dissemination	Neutralize enemy leadership
OPERATIONAL OBJECTIVES			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Defeat air/space forces	7.60	1	9	3	3	1																	
Defeat air defense forces	6.00	2														1				9	9	3	
Prevent sortie generation	7.60	3					3	3	3	3				1	1	1							
Defeat ground forces	5.33	4				1									1	3	3	9	3				
Defeat naval forces	1.73	5				1				1	9				1	1							
Disrupt military support basis	1.73	6										1	3	1	3	3							
Disrupt economic support basis	0.40	7										3	3			3							
Disrupt political base	2.80	8				1		1					1	3		3							9
Disrupt C4I	4.53	9	1	1		3				1			1			3		1	1	1	1	3	3
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
OT QFD Total			72.93	27.33	22.80	31.07	22.80	25.60	22.80	29.07	15.60	2.93	13.73	17.73	19.87	59.73	16.00	52.53	20.53	58.53	58.53	31.60	38.80
OT Rank			1	10	12	8	12	11	12	9	19	21	20	17	16	2	18	5	15	3	3	7	6

Next, the MAA phase transforms the operational tasks to *Whats* and relates them to functions. This step deviates from the original QFD scoring system of 9-3-1-0 to use a grading scale. The question asked while scoring relationships is: "*Given our operational concepts and senior leadership direction, how well does the CAF perform the function of*

_____ *to accomplish the task of* _____?" (HQ ACC, MIP Handbook, 1998: A-7). The basic scoring guidelines used are provided in the ACC Modernization Planning Process MIP handbook's QFD scoring appendix (HQ ACC, MIP Handbook, 1998: A-9):

- A – 90% or more of the required capability to perform the function when accomplishing the task
- B – 80% to 89% of the required capability to perform the function when accomplishing the task
- C – 70% to 79% of the required capability to perform the function when accomplishing the task
- D – 60% to 69% of the required capability to perform the function when accomplishing the task
- F – 59% or less of the required capability to perform the function when accomplishing the task
- Z – The function is not applicable to the task.

For the complete MTW and SSC operational task versus function matrix, Table 24 below lists the fill rate for each type of score.

Table 24: ACC Function Scoring Breakout

SCORE CATEGORY	NUMERICAL EQUIVALENCE	# OF SCORE IN MATRIX	% OF EACH TYPE OF SCORE
A	1	309	39.4
B	2	275	35.1
C	3	62	7.9
D	5	32	4.1
F	9	11	1.4
Z	0	95	12.1
	Total possible	784	

Note that according to this chart, ACC assess that for 74.5% (584) of the function to operational task relationships, they have 80% or more of the required capability to perform the function when accomplishing the task. This implies that the MPP is mainly

concerned with finding solutions for approximately 25% of the CAF force structure. If this is not the case, both the method and the scores for the operational task versus function level should be reevaluated. Please note that while there are twenty-eight functions in the MPP, Tables 25-27 only show fifteen because the chart is quite large. Moreover, the original chart is filled in with the letters corresponding to the grading scale; these charts are used only for computations.

Table 25: MTW Operational Tasks versus Functions

MTW OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
MTW Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Neutralize aircraft in-flight	72.9	1	2	2	2	2	2	1	2	2	1	2	2	5	3	3	2
Neutralize cruise missiles & UAVs in-flight	27.3	2	3	2	2	2	2	1	2	2	1	2	5	5	3	1	5
Neutralize ballistic missiles in-flight	22.8	3	3	3	2	2	2	1	2	2	1		5	3	9	1	9
Neutralize vehicles in space	31.1	4		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Neutralize aircraft, cruise missiles & UAVs on the ground	22.8	5	2	2	2	2	2	1	2	2	2	2	3	3	2	3	1
Neutralize ballistic missiles & support on the ground	25.6	6	3	2	2	2	2	1	2	2	2	3	9	9	2	2	1
Neutralize airfield operating surfaces	22.8	7	1	2	2	2	2	1	2	2	2	2	1	1	3	5	3
Neutralize military support facilities	29.1	8	1	2	2	2	2	1	2	2	1	2	1	1	2	3	1
Neutralize naval vessels	15.6	9	1	1	2	2	2	1	2	2	1	2	2	3	2	3	2
Neutralize industrial production	2.9	10	1	2	2	2	2	1	2	2	1	3	1	2	2	3	2
Neutralize power production	13.7	11	1	2	2	2	2	1	2	2	1	2	1	1	2	3	2
Neutralize WMD production & storage	17.7	12	3	3	2	2	2	1	2	2	1	3	3	5	2	3	5
Neutralize weapons factories & storage sites	19.9	13	1	2	2	2	2	1	2	2	1	2	2	2	2	3	1
Neutralize lines of communication (LOCs)	59.7	14	2	2	2	2	2	1	2	2	1	2	1	2	2	2	3
Neutralize fixed forces	16.0	15	1	2	2	2	2	1	2	2	2	2	2	2	2	3	2
Neutralize advancing combat forces	52.5	16	2	2	2	2	2	1	2	2	2	2	3	5	2	3	3
Neutralize engaged ground forces	20.5	17	2	2	2	2	2	1	2	2	3	3	5	9	3	5	3
Neutralize fixed surface to air threats	58.5	18	2	2	2	2	2	1	2	2	2	3	1	2	3	5	2
Neutralize mobile surface to air threats	58.5	19	3	2	2	2	2	1	2	2	2	3	9	3	5	5	2
Neutralize air defense information collection/dissemination	31.6	20	2	2	2	2	2	1	2	2	1	2	2	2	2	3	2
Neutralize enemy leadership	38.8	21	3	2	2	2	2	1	2	2	1	3	9	5	3	3	5
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MTW FUNCTION QFD			1329.7	1314.9	1290.0	1290.0	1290.0	660.5	1290.0	1290.0	958.4	1467.0	2268.8	2295.0	1866.1	2054.6	1759.4
MTW FUNCTION RANK			9	10	11	11	11	27	11	11	22	8	2	1	4	3	5

Table 26: SSC Operational Tasks versus Functions

SSC OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
SSC Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Enforce Mandates	60.16	1	2		3	2	3	1	1	1	1	2	1	2	2	3	5
Conduct Arms Control Operations	54.16	2	1								1	1					
Combat Terrorism	11.50	3	3		1	1	9	2	1	1	1	1	1	2	2		5
Conduct Counterdrug Operations	6.83	4	1		1		1	1	1			1	1	1	1		
Provide Domestic Aid	1.83	5	1		1	2	1	1	1	1		1					
Provide International Aid	7.16	6	1		1	2	1	1	1	1		1					
Conduct Recovery Operations	10.16	7	1				1		1		1	2	2	2	1	3	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SSC FUNCTION QFD			235.0	0.0	207.8	149.8	310.0	99.0	97.6	80.6	136.0	222.1	98.8	170.5	160.3	211.0	358.3
SSC FUNCTION RANK			5	28	8	15	3	21	23	24	18	6	22	9	10	7	2

Table 27: Total Scores (MTW & SSC) Operational Tasks versus Functions

TOTAL SCORES FOR OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FUNCTION QFD TOTAL			1564.7	1314.9	1497.8	1439.8	1600.0	759.5	1387.6	1370.6	1094.4	1689.2	2367.6	2465.5	2026.4	2265.6	2117.8
FUNCTION RANK TOTAL			10	19	12	15	9	28	16	17	21	8	2	1	5	3	4

Furthermore, the scoring team is only concerned with how well the CAF performs the function to accomplish a task. The team is not interested in how the Air Force as a whole accomplishes the task. "For example, ACC has little or no capability to neutralize vehicles in space…therefore, all functions should rate highly against the neutralize space vehicles task. The CAF does not do it very well (or at all) but it is not an area that ACC wishes to emphasize for modernization investment at this time" (HQ ACC, MIP Handbook, 1998: A-7). Unfortunately, this perspective biases the evaluation of the functions. If a function is not important, it should not be included in the matrix.

Although the example terminates at this point, the MPP continues with two more phases. The second phase, the MNA, develops mission needs and assesses how well the Air Force currently executes them. "A need is a deficient capability described with measures of effectiveness" (HQ ACC, MIP Handbook, 1998: A-9). The MNA phase is an effort to determine how well the Air Force can accomplish its tasks. During this phase, QFD is used to score the functions developed in the MAA phase to the needs. The MNA is also the phase in which the weapons systems platforms are addressed. The results of the platform evaluations are scores of the relative importance of improving specific platform or system capabilities; this scoring is *not* accomplished using standard QFD methods (HQ ACC, MIP Handbook, 1998: A-11). The third phase, the MSA identifies materiel and non-materiel solutions for improving the execution of the needs. The solutions could be repairs, modifications or new programs designed to help correct the capability shortfalls identified during the MNA (HQ ACC, MIP Handbook, 1998: A-13). The MSA phase identifies the potential solutions to meet ACC needs and evaluates the benefit (contribution to combat capability) and cost of each solution to determine the best investment strategy.

ACC Fix 1: Normalization

Normalization may be applied to any existing QFD matrices. Recall, it is assumed that the customer demands are on a ratio scale with the admissible transformation, $\phi(x) = \alpha x$, $\alpha > 0$, thus the attached importance scores will still be meaningful on a ratio scale after being multiplied by any real number greater than zero. This implies the importance scores may be normalized to sum to one. However, because the top two HOQs for ACC have been split apart into two weighted categories (see Table 25), MTW and SSC, the weights

for the characteristics in both categories must sum to one. Since MTW is judged to be twice as important as SSC, the weights for MTW campaign objectives should be normalized to sum to 2/3 and the weights for SSC campaign objectives should be normalized to sum to 1/3. The normalization is not applied to the 9-3-1-0 relationship scores; because using numbers the scoring team is comfortable with may offer more accurate results. If an operational objective is strongly related to every campaign objective and scores a 9 in every block of the column for that quality characteristic, the final score for the column will be 9. Normalization would be also be beneficial in comparing QFD to MAVT because the final scores now lie between zero and nine. The scores could be re-scaled to lie between zero and one, which is a common range used for weights in MAVT. Normalization is an important modification to the scores because the breakout of the scores is more apparent to the QFD user because the range of possible scores is known to be 0 to 9. This is more meaningful to the user because it is the same range as the relationships scores inside the HOQ. See Appendix A for the full HOQs for each fix.

Table 28: ACC HOQ 1 Normalized Score Comparison

MTW	Original		Normalized	
OPERATIONAL OBJECTIVES	Score	Rank	Score	Rank
Defeat air/space forces	7.600	1	2.533	1
Defeat air defense forces	6.000	3	2.000	3
Prevent sortie generation	7.600	1	2.533	1
Defeat ground forces	5.333	4	1.778	4
Defeat naval forces	1.733	7	0.578	7
Disrupt military support basis	1.733	7	0.578	7
Disrupt economic support basis	0.400	9	0.133	9
Disrupt political base	2.800	6	0.933	6
Disrupt C4I	4.533	5	1.511	5

There is very little change to the scores for the first HOQ. Normalizing shows that none of the MTW operational objectives significantly dominates the others. With a possible range for scores from 0 to 9, all of the scores are less than three. It can easily be seen that all of the MTW operational objectives are of comparable importance to each other.

Table 29: ACC HOQ 2 Normalized Score Comparison

MTW OPERATIONAL TASK	Original		Normalized	
	Score	Rank	Score	Rank
Neutralize aircraft inflight	72.933	1	1.419	1
Neutralize cruise missiles & UAVs inflight	27.333	10	0.532	10
Neutralize ballistic missiles inflight	22.800	12	0.444	12
Neutralize vehicles in space	31.067	8	0.604	8
Neutralize aircraft, cruise missiles & UAVs on the ground	22.800	12	0.444	12
Neutralize ballistic missiles & support on the ground	25.600	11	0.498	11
Neutralize airfield operating surfaces	22.800	12	0.444	12
Neutralize military support facilities	29.067	9	0.565	9
Neutralize naval vessels	15.600	19	0.304	19
Neutralize industrial production	2.933	21	0.057	21
Neutralize power production	13.733	20	0.267	20
Neutralize WMD production & storage	17.733	17	0.345	17
Neutralize weapons factories & storage sites	19.867	16	0.387	16
Neutralize lines of communication (LOCs)	59.733	2	1.162	2
Neutralize fixed forces	16.000	18	0.311	18
Neutralize advancing combat forces	52.533	5	1.022	5
Neutralize engaged ground forces	20.533	15	0.399	15
Neutralize fixed surface to air threats	58.533	3	1.139	3
Neutralize mobile surface to air threats	58.533	3	1.139	3
Neutralize air defense information collection/dissemination	31.600	7	0.615	7
Neutralize enemy leadership	38.800	6	0.755	6

The results from the second ACC HOQ indicate that none of the MTW operational tasks significantly outscores the others. The highest score is only 1.419 for *neutralize aircraft in-flight*. This may be related to the sparseness of the matrices. For example, in the MTW operational tasks versus operational objectives HOQ, there are 198 possible relationships and only 28% of them are scored and only 3% of the relationships rate a strong correlation. After a matrix is filled in, a sanity check should be done for each row and column. "There should be none with no relationship or only weak symbols" (Day, 1993:

71). Only weak scores suggest that an operational task (a *How*) has no significant relationship to the operational objective (the *What*). In the second ACC HOQ, there are only six operational tasks with a strong relationship scored against them. As Day points out, this indicates that the other fifteen tasks may need to be reevaluated.

Table 30: ACC HOQ 3 Normalized Score Comparison

FUNCTION	Original		Normalized	
	Score	Rank	Score	Rank
Educate And Train Personnel	1564.733	10	1.926	10
Evaluate And Assess Systems	1314.933	19	1.619	19
Equip And Mobilize Forces	1497.833	12	1.844	12
Develop, Maintain, Recover And Close The Base	1439.833	15	1.772	15
Defend The Base	1600.000	9	1.970	9
Provide Base Services	759.533	28	0.935	28
Provide Base Medical Services	1387.667	16	1.708	16
Provide Base Communication Support	1370.667	17	1.687	17
Sustain Human Performance	1094.400	21	1.347	21
Ingress And Egress	1689.233	8	2.079	8
Find, Fix, Track Target	2367.633	2	2.914	2
Target (ID) Object	2465.567	1	3.035	1
Employ Weapon	2026.467	5	2.495	5
Survive Threats	2265.667	3	2.789	3
Disable Target (Weapon Effectiveness)	2117.800	4	2.607	4
Weapon F2T2 Target Object	1340.267	18	1.650	18
Weapon Ingress And Survive During Employment	1296.333	20	1.596	20
Generate Mission Capable Aircraft	1441.833	13	1.775	13
Maintain Aircraft	1441.833	13	1.775	13
Maintain Support Equipment	885.300	25	1.090	25
Provide Parts Equipment And Consumables	810.533	26	0.998	26
Build Up And Maintain Ammo, Munitions & Fuel Tanks	790.467	27	0.973	27
Provide Surface And Subsurface Target Information	1773.100	7	2.183	7
Provide Airborne Target Information	1084.100	23	1.334	23
Provide Info-Sphere Target Information	1518.133	11	1.869	11
Provide Aerospace Command And Control (C2)	1785.100	6	2.197	6
Conduct Defensive Information Warfare	1090.167	22	1.342	22
Conduct Offensive Information Warfare	891.633	24	1.098	24

One of the problems encountered with QFD is it can result in large scores at the end of the process that have no intuitive meaning. In the last HOQ of the original ACC example, the functions range from *target (ID) object* which scored the highest with 2465.57 to *provide base services* with a score of 759.53 which is less than half of the top scoring

function score. In fact, the top ten ranked function scores are all over twice as large as the score for *provide base services*. However, that observation does not provide much insight into the problem. Normalization provides output that is more meaningful because the numbers are between 0 and 9, which have more intuitive meaning than the original QFD scores. The normalized results of the final HOQ in the ACC example emphasize the small range of the scores for the functions. This may be related to the fact that ACC changes tactics on the last chart. For this level, ACC fills in the relationship matrix by asking the question: "How well must the CAF do the function to accomplish the task" (HQ ACC, MIP Handbook, 1998: A-7). According to Day, the horizontal elements across the top of the HOQ, the *Hows*, must be measurable (Day, 1993: 68). The ACC chart represents "how to do" a task, as opposed to "how to measure it." The scores now represent how well ACC does this function, lower scores mean ACC scores well for this function, because an A (90% or more of the required capability to perform the function when accomplishing the task.) corresponds to a numerical score of 1, B = 2, C = 3, D = 5 and F = 9. Hence, the higher scores are things ACC needs to work on doing better.

ACC Fix 2: Adjust the Scale to be Continuous

The scoring team would have to reassess the scores for the whole QFD process allowing relationships to be scored as any real number between 0 and 9 to adequately demonstrate the effects of adjusting the scale to be continuous. The most important aspect of ensuring a continuous ratio scale is maintained is defining the relationship scores inside the HOQ. The scoring team must agree upon what scoring a 9 actually means. This will be different for each HOQ because it depends on the relationship being scored. Once one level is defined for a HOQ, it will provide a baseline for the other scores within the HOQ.

1. A score may be any real number from 0 to 9. For this step, use the scale the QFD scoring team is most comfortable with; some users prefer a 0 to 5 scale while others may prefer a 0 to 10 scale.
2. 3 is three times more correlated than 1
3. 9 is three times more correlated than 3 and nine times more correlated than 1
4. Scoring a zero means there is no correlation.
5. Scoring nine weak (1) relationships, three moderate (3) relationships, or one strong (9) relationship, are equivalent.

These guidelines can be used to help define what a "9" means. The scores need to be defined based on the situation. The scoring team would then have to agree that the rules listed above actually apply. For example, in the operational task versus function HOQ, using ACC's definitions, the scoring team needs to agree that having only 59% of the required capability to perform the function to accomplish the task is nine times more significant than having 90% or more of the capability and three times more significant than having 70-79% of the required capability to perform a function. Furthermore, it would have to be agreed that having a function move from having 59% or less of the required capability (scoring a 9) to accomplish a task to having 65-75% (scoring a 5) of the capability is equally as important as moving from having 65-75% of the required capability to accomplish a task to having 90% or more (scoring a 1) of the capability.

Carefully defining the framework of the QFD process before evaluating the strength of relationships or correlations could drastically improve the foundations of ACC's Modernization Planning Process. It is important to maintain the integrity of the numbers so as to provide an accurate unbiased 25 year roadmap for the Combat Air Forces.

Chapter 5

CONCLUSIONS

QFD is a customer-oriented methodology designed to incorporate quality and customer demands into every phase of a product development process. It is a flexible tool that can be adapted for use for a variety of activities, to include: manufacturing processes, the design of new products, or future planning. QFD was originally intended as an approach to design; it was further developed to help companies develop new products in economically uncertain environments (Akao, 1990: 3). Due to the adaptability of QFD, it has been used by the military and major corporations including include Ford, Chrysler, General Motors, 3M, John Deere, Boeing, Texas Instruments, Westinghouse, and Hewlett Packard (Bahill and Chapman, 1993: 24). ACC uses QFD to identify modernization initiatives for the MPP and to provide traceability from national military strategy down to the lowest level needs of the Air Force. The traceability in the form of the strategy-to-task (STT) hierarchy aids ACC in justifying the allocation of funds.

ACC's implementation of QFD departs from the traditional use of QFD for manufacturing processes to use it as a planning tool. ACC's goal is to incorporate the demands of the Air Force mission into the modernization planning effort. The framework for ACC's interpretation of QFD is the STT hierarchy. ACC uses QFD to identify and quantify current deficiencies and quantify the value of alternative future solutions. This has led to the investigation of problems with QFD, both generally and with how ACC employs it.

In order to implement QFD, assumptions are required to ensure the feasibility of the process. One crucial assumption is the scale of the numbers for the customer demand importance scores. In order for comparisons to be made between the customer demand importance scores and mathematical transformations to be performed upon them, the scale of the scores must be ratio. This assumption paves the way for the mathematical computations required to prioritize alternatives in QFD. Unfortunately, the assumptions are necessary, but not sufficient for the scores in QFD to remain meaningful on a ratio scale after transformations have been performed. A set of rules has been established to provide guidelines for building and scoring QFD matrices.

RULES FOR QFD

1. Assume the importance scores for the customer demands are on a ratio scale.
2. Normalize the scores so they sum to one and can be used as weights.
3. Ensure the relationship scoring system is on a ratio scale.
    a. A score may be any real number from 0 to 9.
    b. 3 is three times more correlated than 1.
    c. 9 is three times more correlated than 3 and nine times more correlated than 1.
    d. Scoring a zero means there is no correlation.
    e. Scoring nine weak (1) relationships, three moderate (3) relationships, or one strong (9) relationship, are equivalent.
4. The final scores from one HOQ are ratio *if* the customer demands are all equally important (i.e. the customer demands all score the same importance weight) *and* all of the rules above have been strictly followed.

5. Transform the scores from one HOQ into weights for another providing the scores are on a ratio scale.
6. Remember that the final scores are only a *recommendation*. "The column weights that are calculated during the development of the QFD matrix *should not* be used to determine priority items. They represent an artificial number and do not consider key issues" (Day, 1993: 106).

The rules may seem quite strict; however, it has been established that in order to use the scores out of one HOQ as weights in another, they must be on a ratio scale and unless these rules are followed, the scores are meaningless. It has also been established that scores out of one HOQ are on an interval scale, which indicates that ratios of differences between scores may be compared, and that the rank of the alternatives is accurate. However, when linking houses, even by establishing merely that the scores are ordinal and consistent throughout the HOQ it has been shown that there is no guarantee the final results are also ordinal and consistent. This suggests that the results of a QFD matrix should not be taken as concrete data. It is important to remember rule six, the final scores are only a recommendation. A decision maker should use his experience and intuition in conjunction with the analysis to make any decisions that might have significant consequences.

Recommendations

QFD was originally intended as an approach to design. Its purpose is to ensure quality throughout each stage of a product development process; the main goal of QFD is to satisfy the consumer by translating the customer demands into design targets and quality

assurance points (Akao, 1990; 3). QFD was not designed as a planning process in the sense that ACC views planning. QFD is aimed at planning one specific product whereas ACC uses it as a primary input to their analytical system for quantifying the military worth of modernization initiatives (solutions) which in turn drives ACC's force allocation for the next 25 years (HQ ACC, MIP Handbook, 1998: 12-13). ACC uses QFD in building an analytical framework for the MPP. However, the results of QFD are not intended for use as anything more than a general *guideline* for choosing priority items.

The MPP is a complicated two year process and QFD cannot be repaired or replaced overnight. As a first step towards improving the MPP, it is recommended that the rules above be implemented for scoring the HOQs in ACC's process. The hierarchical structure of STT is a beneficial way of breaking down the complexities of the CAF's force structure. The top few levels, campaign objectives to operational objective to operational tasks work well. However the current method for linking the tasks to functions is biased. A remedy for this would be to treat the top three levels as fundamental objectives. Fundamental objectives are defined as the objectives that reflect what really needs to be accomplished (Clemen, 1996: 44). The objectives should be as useful as possible for creating and evaluating alternatives, identifying decision opportunities and guiding the entire decision making process. The lower levels are comparable to means objectives used in MAVT. Recall means objectives are defined as the objectives that are important because they help achieve other objectives (Clemen, 1996: 44). The means objectives offer guidance about the decision situation, are the means to the achievement of fundamental objectives, and are useful for creating alternatives (Keeney, 1992: 34-35). A network is appropriate for structuring the lower

levels of ACC's process because the functions, needs and solutions (means objectives) can be linked to several objectives on the higher levels (fundamental objectives). Approach from the bottom up, starting with matching needs to functions and in turn matching functions to operational tasks. Furthermore, a network format could be beneficial in creating new solutions. Restructuring the STT hierarchy slightly could lead to transforming the analytical framework for the MPP into MAVT or a similar methodology.

Future Research

ACC could continue to use QFD, linking houses and using the final scores in a mathematical program if there were some way to convert the column scores out of one HOQ to a ratio scale. Further research into this area might be beneficial to numerous users of QFD. Decision analysis techniques such as MAVT merit a closer look for use with ACC's planning efforts to potentially provide a more traceable, defendable process for prioritizing modernization initiatives.

APPENDIX A: QFD MATRICES FOR EXAMPLES IN CHAPTER 4

QFD Example from Bahill and Chapman (no modifications)

Table 31: Customer Demands versus Quality Characteristics

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (1 to 10)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	10	9	3			1			5	9		
Retains Shape	4			1		1	3	9	1	1		
Stays Put	4						3	3				
Hygienic	7	1	9							9		
Squeezable	4			9		1		3		1		
Easy Open	6	1			9					3		
No Waste	6	3	1	3		9		1				
Small Footprint	5						9	1				
Reasonable Cost	9								1	3	9	
Attractive Container	8	3					1	3	9	1	9	
Company												
Time to Market	5								1	3	3	9
Return on Investment	9									3	9	3
Score		145	99	58	54	72	77	95	140	256	249	72
Rank		3	5	10	11	8	7	6	4	1	2	8

(Bahill and Chapman, 1993: 27)

Table 32: Quality Characteristics versus Product Characteristics

QUALITY CHARACTERISTICS V. PRODUCT CHARACTERISTICS	Weights	Double Lead Thread	Size of Hole in Tip	Material Thickness	Material Type	Size of Dashpot	Viscosity of Dashpot	Weight of Container	Size of Container	Printing on Label	Shape of Container
Amount of Mess	145		1	1	3	3	3				
Amount of Pull-back	99		3	3	9	3	9				
Amount of Pressure	58		3	3	9		9				
Amount of Effort	54	9	1		1						
Amount of Waste	72		3	1	3		1		3		1
Counter space	77							3	9	1	9
Amount of Deformation	95		1	1	9				1		1
Pleasing Appearance	140				1				3	9	3
Cost to Produce	256			1	9	1	3	1	3	3	9
Selling Price	249			1	3	1	1		1	3	3
Time to Develop	72				3	1	3			1	3
Score		486	981	1288	6380	1309	3153	487	2441	2924	4547
Rank		10	8	7	1	6	3	9	5	4	2

(Bahill and Chapman, 1993: 30)

Table 33: Product Characteristics versus Manufacturing Processes

PRODUCT CHARACTERISTICS V. MANUFACTURING PROCESSES	Weights	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label
Double Lead Thread	486		9	9	3		1	1		
Size of Hole in Tip	981		9	9	3		9			
Material Thickness	1288			9					3	
Material Type	6380		1	9	1	3		1	9	3
Size of Dashpot	1309		3			1			3	
Viscosity of Dashpot	3153		9	9	3				3	
Weight of Container	487		3			1				
Size of Container	2441		9			1	3		1	3
Printing on Label	2924									9
Shape of Container	4547		9	9	3	3			3	9
Score			116240	151515	33881	37018	16638	6866	90752	93702
Rank			2	1	6	5	7	8	4	3

(Bahill and Chapman, 1993: 31)

Table 34: Manufacturing Processes versus Quality Controls

MANUFACTURING PROCESSES V. QUALITY CONTROLS	Weights	Mold Dimensions	Material Controls	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flow rate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygiene Controls
Molding Process (Cap, Body, Bottom)															
Create Mold	116240	9													1
Blow Material	151515			9	3	3									
Remove Container	33881	3													1
Insert and Bond Liner	37018	1					9				1		1		
Inserting Toothpaste	16638							9							9
Screwing on Top	6866	1							9						3
Ultrasonic Weld Bottom	90752										3	3	9		1
Pasting or Printing Label	93702													9	1
Score		1191687		1363635	454545	454545	333162	149742	61794		309274	272256	853786	843318	504915
Rank		2		1	6	6	8	11	12		9	10	3	4	5

(Bahill and Chapman, 1993: 32)

ToothBrite Fix 1: Normalization

Table 35: Normalization – Customer Demands versus Quality Characteristics

CUSTOMER DEMANDS v. QUALITY CHARACTERISTICS	Importance (0 to 1)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	0.130	9	3			1			5	9		
Retains Shape	0.052			1		1	3	9	1	1		
Stays Put	0.052						3	3				
Hygienic	0.091	1	9							9		
Squeezable	0.052			9		1		3		1		
Easy Open	0.078	1			9					3		
No Waste	0.078	3	1	3		9		1				
Small Footprint	0.065						9	1				
Reasonable Cost	0.117								1	3	9	
Attractive Container	0.104	3					1	3	9	1	9	
Company												
Time to Market	0.065								1	3	3	9
Return on Investment	0.117									3	9	3
Score		1.883	1.286	0.753	0.701	0.935	1.000	1.234	1.818	3.325	3.234	0.935
Rank		3	5	10	11	8	7	6	4	1	2	8

Table 36: Normalization – Quality Characteristics versus Product Characteristics

QUALITY CHARACTERISTICS V. PRODUCT CHARACTERISTICS	Weights	Double Lead Thread	Size of Hole in Tip	Material Thickness	Material Type	Size of Dash-pot	Viscosity of Dash-pot	Weight of Container	Size of Container	Printing on Label	Shape of Container
Amount of Mess	0.110		1	1	3	3	3				
Amount of Pull-back	0.075		3	3	9	3	9				
Amount of Pressure	0.044		3	3	9		9				
Amount of Effort	0.041	9	1		1						
Amount of Waste	0.055		3	1	3		1		3		1
Counter space	0.058							3	9	1	9
Amount of Deformation	0.072		1	1	9				1		1
Pleasing Appearance	0.106				1				3	9	3
Cost to Produce	0.194			1	9	1	3	1	3	3	9
Selling Price	0.189			1	3	1	1		1	3	3
Time to Develop	0.055				3	1	3			1	3
Score		0.369	0.745	0.978	4.844	0.994	2.394	0.370	1.853	2.220	3.453
Rank		10	8	7	1	6	3	9	5	4	2

Table 37: Normalization –Product Characteristics versus Manufacturing Processes

PRODUCT CHARACTERISTICS V. MANUFACTURING PROCESSES	Weights	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label
Double Lead Thread	0.020		9	9	3		1	1		
Size of Hole in Tip	0.041		9	9	3		9			
Material Thickness	0.054			9					3	
Material Type	0.266		1	9	1	3		1	9	3
Size of Dash-pot	0.055		3			1			3	
Viscosity of Dash-pot	0.131		9	9	3				3	
Weight of Container	0.020		3			1				
Size of Container	0.102		9			1	3		1	3
Printing on Label	0.122									9
Shape of Container	0.189		9	9	3	3			3	9
Score			4.844	6.314	1.412	1.543	0.693	0.286	3.782	3.905
Rank			2	1	6	5	7	8	4	3

Table 38: Normalization –Manufacturing Processes versus Quality Control

MANUFACTURING PROCESSES V. QUALITY CONTROLS	Weights	Mold Dimensions	Material Controls	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flow rate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygiene Controls
Molding Process (Cap, Body, Bottom)															
Create Mold	0.213	9													1
Blow Material	0.277			9	3	3									
Remove Container	0.062	3													1
Insert and Bond Liner	0.068	1					9				1		1		
Inserting Toothpaste	0.030							9							9
Screwing on Top	0.013	1							9						3
Ultrasonic Weld Bottom	0.166										3	3	9		1
Pasting or Printing Label	0.171													9	1
Score		2.180		2.495	0.832	0.832	0.610	0.274	0.113		0.566	0.498	1.562	1.543	0.924
Rank		2		1	6	6	8	11	12		9	10	3	4	5

ToothBrite Fix 2: Adjust the Scale of the Relationship Scores to Ratio

Table 39: Ratio – Customer Demands versus Quality Characteristics

CUSTOMER DEMANDS V. QUALITY CHARACTERISTICS	Importance (0 to 1)	Amount of Mess	Amount of Pull-back	Amount of Pressure	Amount of Effort	Amount of Waste	Counter space	Amount of Deformation	Pleasing Appearance	Cost to Produce	Selling Price	Time to Develop
Customer												
Neatness												
Tidy Tip	0.130	7	3			1			5	9		
Retains Shape	0.052			1		1.5	4	9	1	0.5		
Stays Put	0.052						3	5				
Hygienic	0.091	1	9							7		
Squeezable	0.052			8		1		5		1		
Easy Open	0.078	1			6.5					3		
No Waste	0.078	5	1	3		9		2				
Small Footprint	0.065						6	1				
Reasonable Cost	0.117								1	3	9	
Attractive Container	0.104	3					1	3	9	0.5	9	
Company												
Time to Market	0.065								1	3	2	7
Return on Investment	0.117									3	9	3
Score		1.779	1.286	0.701	0.506	0.961	0.857	1.519	1.818	3.065	3.169	0.805
Rank		4	6	10	11	7	8	5	3	2	1	9

Table 40: Ratio –Quality Characteristics versus Product Characteristics

QUALITY CHARACTERISTICS V. PRODUCT CHARACTERISTICS	Weights	Double Lead Thread	Size of Hole in Tip	Material Thickness	Material Type	Size of Dash-pot	Viscosity of Dash-pot	Weight of Container	Size of Container	Printing on Label	Shape of Container
Amount of Mess	0.108		1	1	3	5	3				
Amount of Pull-back	0.078		4	3	7	3	9				
Amount of Pressure	0.043		3	3	9		6				
Amount of Effort	0.031	9	1		2						
Amount of Waste	0.058		3	1	3		1		3		0.5
Counter space	0.052							3	8	1	9
Amount of Deformation	0.092		1	1	8				1		1
Pleasing Appearance	0.11				1				4	9	3
Cost to Produce	0.186			2	7	1	3	1	3	5	9
Selling Price	0.192			1	3	1	1		0.5	3	4
Time to Develop	0.049				4	1	3			1	3
Score		0.277	0.846	1.185	4.415	1.202	2.238	0.342	1.780	2.603	3.513
Rank		10	8	7	1	6	4	9	5	3	2

Table 41: Ratio – Product Characteristics versus Manufacturing Processes

PRODUCT CHARACTERISTICS V. MANUFACTURING PROCESSES	Weights	Molding Process (Cap, Body, Bottom)	Create Mold	Blow Material	Remove Container	Insert and Bond Liner	Inserting Toothpaste	Screwing on Top	Ultrasonic Weld Bottom	Pasting or Printing Label
Double Lead Thread	0.015		9	8	4		1	0.5		
Size of Hole in Tip	0.046		9	7	3		9			
Material Thickness	0.064			9					4	
Material Type	0.240		2	7	1	3		1	9	3
Size of Dash-pot	0.065		3			1			5	
Viscosity of Dash-pot	0.122		9	8	3				3	
Weight of Container	0.019		5			1				
Size of Container	0.097		9			1	5		2	3
Printing on Label	0.141									7
Shape of Container	0.191		9	6.5	5	3			3	8
Score			5.002	4.915	1.757	1.473	0.913	0.247	3.875	3.527
Rank			1	2	5	6	7	8	3	4

Table 42: Ratio –Manufacturing Processes versus Quality Controls

MANUFACTURING PROCESSES V. QUALITY CONTROLS	Weights	Mold Dimensions	Material Controls	Temperature	Pressure	Time	Liner Attachment Inspection	Toothpaste Flow rate	Cap Attachment Torque	Welding Controls	Intensity	Duration	Pressure	Labeling Pressure	Cleanliness and Hygiene Controls
Molding Process (Cap, Body, Bottom)															
Create Mold	0.230	9													1
Blow Material	0.226			9	5	3									
Remove Container	0.081	3													2
Insert and Bond Liner	0.068	2					7				1		1		
Inserting Toothpaste	0.042							7							8
Screwing on Top	0.011	1							7						5
Ultrasonic Weld Bottom	0.178										5	3	9		1
Pasting or Printing Label	0.162													9	1
Score		2.458		2.038	1.132	0.679	0.475	0.294	0.080		0.960	0.535	1.674	1.462	1.127
Rank		1		2	5	8	10	11	12		7	9	3	4	6

ACC Example (no modifications)

Table 43: Objective Weights

Campaign or Regional Objective	Weight
Major Theater of War (MTW)	2
Small Scale Conflict (SSC)	1

Table 44: MTW Campaign Objectives versus Operational Objectives

MTW CAMPAIGN OBJECTIVES V. OPERATIONAL OBJECTIVES	Rank	Initial Weight	Operational Objectives	Defeat air/space forces	Defeat air defense forces	Prevent sortie generation	Defeat ground forces	Defeat naval forces	Disrupt military support basis	Disrupt economic support basis	Disrupt political base	Disrupt C4I
Campaign Objectives				1	2	3	4	5	6	7	8	9
Establish aerospace supremacy	5	0.667	1	9	9	9						3
Establish maritime supremacy	1	0.133	2					9				3
Establish ground supremacy	4	0.533	3				9					3
Counter weapons of mass destruction	4	0.533	4	3		3	1	1	1		3	1
Eliminate war making will/ability	1	0.133	5						9	3	9	
				1	2	3	4	5	6	7	8	9
OO QFD Total				7.600	6.000	7.600	5.333	1.733	1.733	0.400	2.800	4.533
OO Rank				1	3	1	4	7	7	9	6	5

Table 45: SSC Regional Objectives versus Operational Objectives

SSC REGIONAL OBJECTIVES V. OPERATIONAL OBJECTIVES	Rank	Initial Weight	Operational Objectives	Disrupt State Aggression	Counter WMD Proliferation	Disrupt Unlawful Activities	Provide Humanitarian Assistance
Regional Objectives				1	2	3	4
Protect Vital National Interests	3	0.500	1	3	9	1	
Protect Important National Interests	2	0.333	2	9	3	3	1
Protect Humanitarian National Interests	1	0.167	3	1		1	9
				1	2	3	4
RO QFD Total				4.667	5.500	1.667	1.833
RO Rank				2	1	4	3

Table 46: MTW Operational Objectives versus Operational Tasks

MTW OPERATIONAL OBJECTIVES V. OPERATIONAL TASKS	Rank	Operational Tasks	Neutralize aircraft in-flight	Neutralize cruise missiles & UAVs in-flight	Neutralize ballistic missiles in-flight	Neutralize vehicles in space	Neutralize aircraft, cruise missiles and UAVs on the ground	Neutralize ballistic missiles & support on the ground	Neutralize airfield operating surfaces	Neutralize military support facilities	Neutralize naval vessels	Neutralize industrial production	Neutralize power production	Neutralize WMD production & storage	Neutralize weapons factories & storage sites	Neutralize lines of communication (LOCs)	Neutralize fixed forces	Neutralize advancing combat forces	Neutralize engaged ground forces	Neutralize fixed surface to air threats	Neutralize mobile surface to air threats	Neutralize air defense information collection/dissemination	Neutralize enemy leadership
Operational Objectives			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Defeat air/space forces	7.60	1	9	3	3	1																	
Defeat air defense forces	6.00	2														1				9	9	3	
Prevent sortie generation	7.60	3					3	3	3	3				1	1	1							
Defeat ground forces	5.33	4				1									1	3	3	9	3				
Defeat naval forces	1.73	5				1				1	9				1	1							
Disrupt military support basis	1.73	6										1	3	1	3	3							
Disrupt economic support basis	0.40	7										3	3			3							
Disrupt political base	2.80	8				1		1					1	3		3							9
Disrupt C4I	4.53	9	1	1		3				1			1			3		1	1	1	1	3	3
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
OT QFD Total			72.93	27.33	22.80	31.07	22.80	25.60	22.80	29.07	15.60	2.93	13.73	17.73	19.87	59.73	16.00	52.53	20.53	58.53	58.53	31.60	38.80
OT Rank			1	10	12	8	12	11	12	9	19	21	20	17	16	2	18	5	15	3	3	7	6

Table 47: SSC Operational Objectives versus Operational Tasks

SSC OPERATIONAL OBJECTIVES V. OPERATIONAL TASKS	Rank	Operational Tasks	Enforce Mandates	Conduct Arms Control Operations	Combat Terrorism	Conduct Counterdrug Operations	Provide Domestic Aid	Provide International Aid	Conduct Recovery Operations
Operational Objectives			1	2	3	4	5	6	7
Disrupt State Aggression	4.67	1	9	1	1				1
Counter WMD Proliferation	5.50	2	3	9					
Disrupt Unlawful Activities	1.67	3	1		3	3		1	
Provide Humanitarian Assistance	1.83	4			1	1	1	3	3
			1	2	3	4	5	6	7
SSC OT Total			60.166	54.166	11.500	6.833	1.833	7.166	10.166
SSC OT Rank			1	2	3	6	7	5	4

Table 48: MTW Operational Tasks versus Functions

MTW OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover & Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
MTW Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Neutralize aircraft in-flight	72.9	1	2	2	2	2	2	1	2	2	1	2	2	5	3	3	2
Neutralize cruise missiles & UAVs in-flight	27.3	2	3	2	2	2	2	1	2	2	1	2	5	5	3	1	5
Neutralize ballistic missiles in-flight	22.8	3	3	3	2	2	2	1	2	2	1		5	3	9	1	9
Neutralize vehicles in space	31.1	4		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Neutralize aircraft, cruise missiles & UAVs on the ground	22.8	5	2	2	2	2	2	1	2	2	2	2	3	3	2	3	1
Neutralize ballistic missiles & support on the ground	25.6	6	3	2	2	2	2	1	2	2	2	3	9	9	2	2	1
Neutralize airfield operating surfaces	22.8	7	1	2	2	2	2	1	2	2	2	2	1	1	3	5	3
Neutralize military support facilities	29.1	8	1	2	2	2	2	1	2	2	1	2	1	1	2	3	1
Neutralize naval vessels	15.6	9	1	1	2	2	2	1	2	2	1	2	2	3	2	3	2
Neutralize industrial production	2.9	10	1	2	2	2	2	1	2	2	1	3	1	2	2	3	2
Neutralize power production	13.7	11	1	2	2	2	2	1	2	2	1	2	1	1	2	3	2
Neutralize WMD production & storage	17.7	12	3	3	2	2	2	1	2	2	1	3	3	5	2	3	5
Neutralize weapons factories & storage sites	19.9	13	1	2	2	2	2	1	2	2	1	2	2	2	2	3	1
Neutralize lines of communication (LOCs)	59.7	14	2	2	2	2	2	1	2	2	1	2	1	2	2	2	3
Neutralize fixed forces	16.0	15	1	2	2	2	2	1	2	2	2	2	2	2	2	3	2
Neutralize advancing combat forces	52.5	16	2	2	2	2	2	1	2	2	2	2	3	5	2	3	3
Neutralize engaged ground forces	20.5	17	2	2	2	2	2	1	2	2	3	3	5	9	3	5	3
Neutralize fixed surface to air threats	58.5	18	2	2	2	2	2	1	2	2	2	3	1	2	3	5	2
Neutralize mobile surface to air threats	58.5	19	3	2	2	2	2	1	2	2	2	3	9	3	5	5	2
Neutralize air defense information collection/dissemination	31.6	20	2	2	2	2	2	1	2	2	1	2	2	2	2	3	2
Neutralize enemy leadership	38.8	21	3	2	2	2	2	1	2	2	1	3	9	5	3	3	5
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MTW FUNCTION QFD			1329.7	1314.9	1290.0	1290.0	1290.0	660.5	1290.0	1290.0	958.4	1467.0	2268.8	2295.0	1866.1	2054.6	1759.4
MTW FUNCTION RANK			9	10	11	11	11	27	11	11	22	8	2	1	4	3	5

(There are twenty-eight functions in all the chart only shows fifteen because the chart is too large.)

Table 49: SSC Operational Tasks versus Functions

SSC OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
SSC Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Enforce Mandates	60.16	1	2		3	2	3	1	1	1	1	2	1	2	2	3	5
Conduct Arms Control Operations	54.16	2	1								1	1					
Combat Terrorism	11.50	3	3		1	1	9	2	1	1	1	1	1	2	2		5
Conduct Counterdrug Operations	6.83	4	1		1		1	1	1			1	1	1	1		
Provide Domestic Aid	1.83	5	1		1	2	1	1	1	1		1					
Provide International Aid	7.16	6	1		1	2	1	1	1	1		1					
Conduct Recovery Operations	10.16	7	1				1		1		1	2	2	2	1	3	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SSC FUNCTION QFD			235.0	0.0	207.8	149.8	310.0	99.0	97.6	80.6	136.0	222.1	98.8	170.5	160.3	211.0	358.3
SSC FUNCTION RANK			5	28	8	15	3	21	23	24	18	6	22	9	10	7	2

Table 50: Total Scores (MTW & SSC) Operational Tasks versus Functions

TOTAL SCORES FOR OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FUNCTION QFD TOTAL			1564.7	1314.9	1497.8	1439.8	1600.0	759.5	1387.6	1370.6	1094.4	1689.2	2367.6	2465.5	2026.4	2265.6	2117.8
FUNCTION RANK TOTAL			10	19	12	15	9	28	16	17	21	8	2	1	5	3	4

ACC Normalized

Table 51: Objective Weights

Campaign or Regional Objective	Weight
Major Theater of War (MTW)	2/3
Small Scale Conflict (SSC)	1/3

Table 52: Normalization – MTW Campaign Objectives versus Operational Objectives

MTW CAMPAIGN OBJECTIVES v. OPERATIONAL OBJECTIVES	Rank	Initial Weight	Operational Objectives	Defeat air/space forces	Defeat air defense forces	Prevent sortie generation	Defeat ground forces	Defeat naval forces	Disrupt military support basis	Disrupt economic support basis	Disrupt political base	Disrupt C4I
Campaign Objectives				1	2	3	4	5	6	7	8	9
Establish aerospace supremacy	5	0.222	1	9	9	9						3
Establish maritime supremacy	1	0.044	2					9				3
Establish ground supremacy	4	0.178	3				9					3
Counter weapons of mass destruction	4	0.178	4	3		3	1	1	1		3	1
Eliminate war making will/ability	1	0.044	5						9	3	9	
				1	2	3	4	5	6	7	8	9
OO QFD Total				2.533	2.000	2.533	1.778	0.578	0.578	0.133	0.933	1.511
OO Rank				1	3	1	4	7	7	9	6	5

Table 53: Normalization – SSC Regional Objectives versus Operational Objectives

SSC REGIONAL OBJECTIVES V. OPERATIONAL OBJECTIVES	Rank	Initial Weight	Operational Objectives	Disrupt State Aggression	Counter WMD Proliferation	Disrupt Unlawful Activities	Provide Humanitarian Assistance
Regional Objectives				1	2	3	4
Protect Vital National Interests	3	0.167	1	3	9	1	
Protect Important National Interests	2	0.111	2	9	3	3	1
Protect Humanitarian National Interests	1	0.056	3	1		1	9
				1	2	3	4
RO QFD Total				1.556	1.833	0.556	0.611
RO Rank				2	1	4	3

Table 54: Normalization – MTW Operational Objectives versus Operational Tasks

MTW OPERATIONAL OBJECTIVES V. OPERATIONAL TASKS	Rank	Operational Tasks	Neutralize aircraft in-flight	Neutralize cruise missiles & UAVs in-flight	Neutralize ballistic missiles in-flight	Neutralize vehicles in space	ground	Neutralize ballistic missiles & support on the ground	Neutralize airfield operating surfaces	Neutralize military support facilities	Neutralize naval vessels	Neutralize industrial production	Neutralize power production	Neutralize WMD production & storage	Neutralize weapons factories & storage sites	Neutralize lines of communication (LOCs)	Neutralize fixed forces	Neutralize advancing combat forces	Neutralize engaged ground forces	Neutralize fixed surface to air threats	Neutralize mobile surface to air threats	collection/dissemination	Neutralize enemy leadership
OPERATIONAL OBJECTIVES			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Defeat air/space forces	0.148	1	9	3	3	1																	
Defeat air defense forces	0.117	2														1				9	9	3	
Prevent sortie generation	0.148	3					3	3	3	3				1	1	1							
Defeat ground forces	0.104	4				1									1	3	3	9	3				
Defeat naval forces	0.034	5				1				1	9				1	1							
Disrupt military support basis	0.034	6										1	3	1	3	3							
Disrupt economic support basis	0.008	7										3	3			3							
Disrupt political base	0.054	8				1		1					1	3		3							9
Disrupt C4I	0.088	9	1	1		3				1			1			3		1	1	1	1	3	3
			1	2	3	4	5	6	7	8	9	1	1	1	1	1	1	1	1	1	1	2	2
OT QFD Total			1.419	0.532	0.444	0.604	0.444	0.498	0.444	0.565	0.304	0.057	0.267	0.345	0.387	1.162	0.311	1.022	0.399	1.139	1.139	0.615	0.755
OT Rank			1	10	12	8	12	11	12	9	19	21	20	17	16	2	18	5	15	3	3	7	6

Table 55: Normalization – SSC Operational Objectives versus Operational Tasks

SSC OPERATIONAL OBJECTIVES V. OPERATIONAL TASKS	Rank	Operational Tasks	Enforce Mandates	Conduct Arms Control Operations	Combat Terrorism	Conduct Counterdrug Operations	Provide Domestic Aid	Provide International Aid	Conduct Recovery Operations
Operational Objectives			1	2	3	4	5	6	7
Disrupt State Aggression	0.091	1	9	1	1				1
Counter WMD Proliferation	0.107	2	3	9					
Disrupt Unlawful Activities	0.032	3	1		3	3		1	
Provide Humanitarian Assistance	0.036	4			1	1	1	3	3
			1	2	3	4	5	6	7
SSC OT Total			1.1706	1.0538	0.2237	0.1329	0.0357	0.1394	0.1978
SSC OT Rank			1	2	3	6	7	5	4

Table 56: Normalization – MTW Operational Tasks versus Functions

MTW OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover & Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
MTW Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Neutralize aircraft in-flight	0.090	1	2	2	2	2	2	1	2	2	1	2	2	5	3	3	2
Neutralize cruise missiles & UAVs in-flight	0.034	2	3	2	2	2	2	1	2	2	1	2	5	5	3	1	5
Neutralize ballistic missiles in-flight	0.028	3	3	3	2	2	2	1	2	2	1		5	3	9	1	9
Neutralize vehicles in space	0.038	4		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Neutralize aircraft, cruise missiles & UAVs on the ground	0.028	5	2	2	2	2	2	1	2	2	2	2	3	3	2	3	1
Neutralize ballistic missiles & support on the ground	0.032	6	3	2	2	2	2	1	2	2	2	3	9	9	2	2	1
Neutralize airfield operating surfaces	0.028	7	1	2	2	2	2	1	2	2	2	2	1	1	3	5	3
Neutralize military support facilities	0.036	8	1	2	2	2	2	1	2	2	1	2	1	1	2	3	1
Neutralize naval vessels	0.019	9	1	1	2	2	2	1	2	2	1	2	2	3	2	3	2
Neutralize industrial production	0.004	10	1	2	2	2	2	1	2	2	1	3	1	2	2	3	2
Neutralize power production	0.017	11	1	2	2	2	2	1	2	2	1	2	1	1	2	3	2
Neutralize WMD production & storage	0.022	12	3	3	2	2	2	1	2	2	1	3	3	5	2	3	5
Neutralize weapons factories & storage sites	0.024	13	1	2	2	2	2	1	2	2	1	2	2	2	2	3	1
Neutralize lines of communication (LOCs)	0.074	14	2	2	2	2	2	1	2	2	1	2	1	2	2	2	3
Neutralize fixed forces	0.020	15	1	2	2	2	2	1	2	2	2	2	2	2	2	3	2
Neutralize advancing combat forces	0.065	16	2	2	2	2	2	1	2	2	2	2	3	5	2	3	3
Neutralize engaged ground forces	0.025	17	2	2	2	2	2	1	2	2	3	3	5	9	3	5	3
Neutralize fixed surface to air threats	0.072	18	2	2	2	2	2	1	2	2	2	3	1	2	3	5	2
Neutralize mobile surface to air threats	0.072	19	3	2	2	2	2	1	2	2	2	3	9	3	5	5	2
Neutralize air defense information collection/dissemination	0.039	20	2	2	2	2	2	1	2	2	1	2	2	2	2	3	2
Neutralize enemy leadership	0.048	21	3	2	2	2	2	1	2	2	1	3	9	5	3	3	5
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MTW FUNCTION QFD			1.64	1.62	1.59	1.59	1.59	0.81	1.59	1.59	1.18	1.81	2.79	2.83	2.30	2.53	2.17
MTW FUNCTION RANK			9	10	11	11	11	27	11	11	22	8	2	1	4	3	5

(There are twenty-eight functions in all the chart only shows fifteen because the chart is too large.)

Table 57: Normalization – SSC Operational Tasks versus Functions

SSC OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
SSC Operational Tasks			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Enforce Mandates	0.074	1	2		3	2	3	1	1	1	1	2	1	2	2	3	5
Conduct Arms Control Operations	0.067	2	1								1	1					
Combat Terrorism	0.014	3	3		1	1	9	2	1	1	1	1	1	2	2		5
Conduct Counterdrug Operations	0.008	4	1		1		1	1	1			1	1	1	1		
Provide Domestic Aid	0.002	5	1		1	2	1	1	1	1		1					
Provide International Aid	0.009	6	1		1	2	1	1	1	1		1					
Conduct Recovery Operations	0.013	7	1				1		1		1	2	2	2	1	3	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SSC FUNCTION QFD			0.29	0.0	0.26	0.18	0.38	0.12	0.12	0.10	0.17	0.27	0.12	0.21	0.20	0.26	0.44
SSC FUNCTION RANK			5	28	8	15	3	21	23	24	18	6	22	9	10	7	2

Table 58: Total Scores (MTW & SSC) Operational Tasks versus Functions

TOTAL SCORES FOR OPERATIONAL TASKS V. FUNCTIONS	Rank	Functions	Educate and Train Personnel	Evaluate and Assess Systems	Equip and Mobilize Forces	Develop, Maintain, Recover and Close the Base	Defend the Base	Provide Base Services	Provide Base Medical Services	Provide Base Communication Support	Sustain Human Performance	Ingress and Egress	Find, Fix, Track Target	Target (ID) Object	Employ Weapon	Survive Threats	Disable Target (Weapon Effectiveness)
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
FUNCTION QFD TOTAL			1.93	1.62	1.84	1.77	1.97	0.93	1.71	1.69	1.35	2.08	2.91	3.04	2.49	2.79	2.61
FUNCTION RANK TOTAL			10	19	12	15	9	28	16	17	21	8	2	1	5	3	4

APPENDIX B: ACRONYMS

ACC	Air Combat Command
ACQ	Acquisitions
AF	Air Force
AFB	Air Force Base
AFDD	Air Force Doctrine Document
AFI	Air Force Instruction
AFIT	Air Force Institute of Technology
AFPD	Air Force Policy Directive
AFRES	Air Force Reserve
AFSPC	Air Force Space Command
ANG	Air National Guard
ASC	Aeronautical Systems Center
CAF	Combat Air Force
CINC	Commander in Chief
DA	Decision Analysis
DPG	Defense Planning Guidance
DR	Requirements Directorate
HOQ	House of Quality
HQ	Headquarters
HQ ACC	Headquarters, Air Combat Command
IR&D	Independent Research and Development

LP	Linear Program
MAA	Mission Area Assessment
MAJCOM	Major Command
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Value Theory
MIP	Modernization Investment Plan
MNA	Mission Needs Analysis
MOE	Measure of Effectiveness
MPP	Modernization Planning Process
MSA	Mission Solution Analysis
MTW	Major Theater of War
OR	Operations Research
PACAF	Pacific Air Forces
POM	Program Objective Memorandum
PPBS	Planning, Programming and Budgeting System
QFD	Quality Function Deployment
SSC	Small Scale Conflict
STT	Strategy to Task
TPIPT	Technical Planning Integrated Product Team
USAFE	United States Air Forces in Europe
VFT	Value Focused Thinking
XR	Development Planning Directorate
XRC	Air Superiority TPIPT

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13. ABSTRACT *(Maximum 200 words)*
The methodology of Quality Function Deployment (QFD) is compared to operations analysis standards. Of special concern is how Air Combat Command (ACC) uses QFD for the Modernization Planning Process (MPP). ACC digresses from the traditional use of QFD for incorporating quality into manufacturing processes to use it as a planning tool. ACC's goal in implementing QFD is to incorporate the demands of the Air Force mission into the modernization planning effort. ACC's use of QFD to identify and quantify current deficiencies and quantify the value of alternative future solutions has led to the investigation of inconsistencies with QFD, both generally and with how ACC employs it. In short, the purpose of this thesis is to improve ACC's current method for optimizing combat capability through both near-term and far-term modifications.

14. SUBJECT TERMS
Quality Function Deployment, Measurement Theory, Multi-Attribute Value Theory

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